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Consolidation of Peat and Organic Soil using Electro-osmosis Treatment

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DECLARATION

To the best of my knowledge and belief, this dissertation contains no material previously published by any other person except where due acknowledgement has been made.

This dissertation contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: 

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PUBLICATIONS

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Consolidation of Peat and Organic Soil Using Electro-osmosis Treatment

ABSTRACT

Peat is highly compressible with weak shear strength making it a soft soil that is subjected to large settlement with load increase. Over the years, various methods of ground improvement such as preloading, deep soil mixing, cement columns, addition of chemical admixtures including electro-osmosis, have been developed to improve peat. Though electro-osmosis has been proven to be a viable method for improvement of clay, limited studies have been carried out on the electro-osmosis of peat. This study aims to investigate the effects of electro-osmosis (EO) on the consolidation of peat and organic soil. The objectives in this research focus on the effects of voltage gradient, radial electrode configuration, pumping intervals of drainage well and polarity reversal.

In order to achieve the objectives, 23 numbers of small scale and 9 numbers of large scale EO tests were conducted on peat and organic soil. During the test duration, surface settlement, volume of water collected, voltage transmitted and current variation in the soil test sample were measured. Moisture content and shear strength of the test samples before and after electro-osmotic consolidation were also obtained.

Small scale one-dimensional EO tests on peat with different voltage gradients indicated a possible optimum voltage gradient of 100V/m resulting in the largest settlement, volume of water collected and strength gain. Furthermore, large scale two-dimensional EO tests also show similar results of the possible optimum voltage gradient of 100V/m. In the large scale one-dimensional EO test, voltage gradient of 80V/m resulted in the highest settlement and volume of water collected. This indicates that for peat, depending on the test configuration, there is an optimum voltage gradient where the largest settlement and highest volume of water collected is achieved. Application of voltage gradient higher than the optimum voltage gradient would not result in larger settlement and volume of water collected in peat.

The square and hexagon electrode configurations were used in this study to investigate the effect of radial electrode configuration in EO consolidation. The EO tests with radial electrode configuration were conducted with voltage gradients ranging from 80 to 120V/m. Based on common perception and existing numerical results, larger settlement as well as higher volume of water collected is expected for the hexagon electrode configuration. However, test results show that the hexagon electrode configuration did not result in significant larger settlement and higher volume of water collected when compared to that of the square electrode configuration.

The 3hr pumping interval of the drainage well resulted in the highest settlement, volume of water removed and strength gain for EO tests on organic soil and peat. Polarity reversal during EO of organic soil and peat resulted in lower differential settlement with a more uniformed settlement profile. However, the magnitude of settlement and strength gain is lower compared to the EO tests without polarity reversal.

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1D	One-dimensional
2D	Two-dimensional
CEC	Cation exchange capacity
DC	Direct current
EO	Electro-osmosis / Electro-osmotic
h	Initial height of soil sample
k_e	Electroosmotic permeability
S_a	Average settlement
ξ	Zeta potential

1 Introduction

1.1 Background

1.1.1 Peat and the Need for Ground Improvement

Peat, which commonly shows high compressibility and low shear strength properties, has drawn continuing interests among researchers. The high compressibility behaviour of peat found in engineering projects led to extensive studies on their engineering properties (Duraisamy *et* al. 2007b). In Malaysia, the total peat coverage is 11.1% of total land, with 4.1% in Peninsula Malaysia and 7.0% in Sabah and Sarawak (Yoshino *et* al. 2010). The state of Sarawak in Malaysia was found to be covered in 16,500km^2 of peat, approximately 13% of the state area (Singh *et* al. 1997). This makes the state of Sarawak the state with the largest coverage of peat in Malaysia.

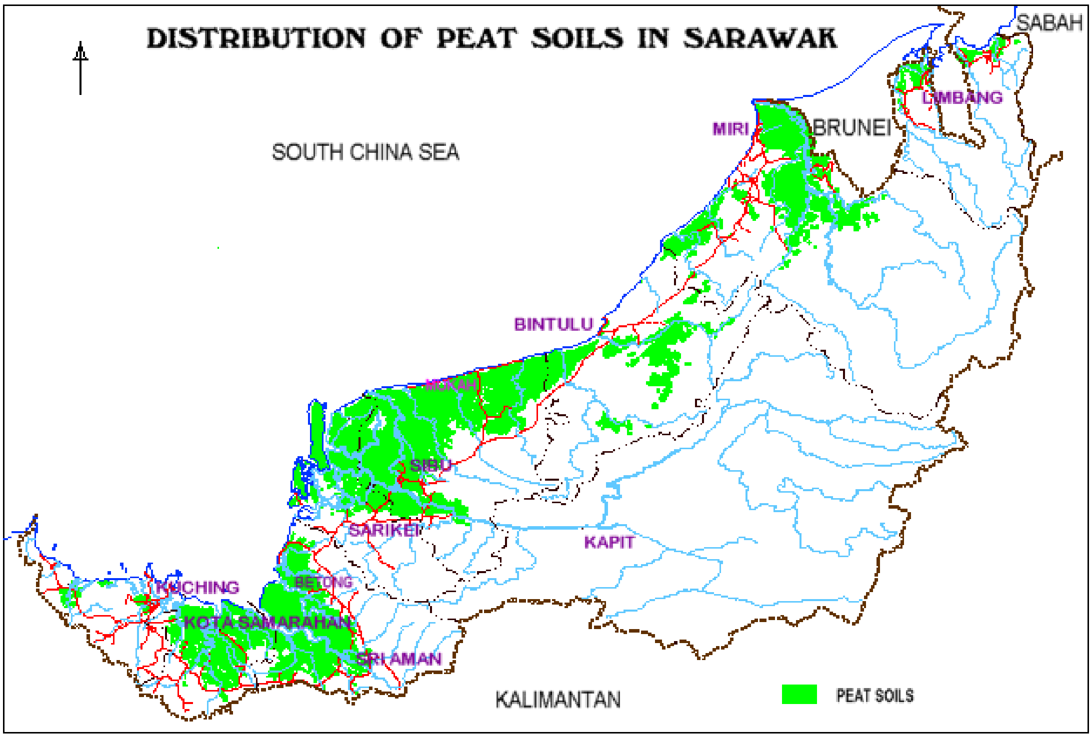
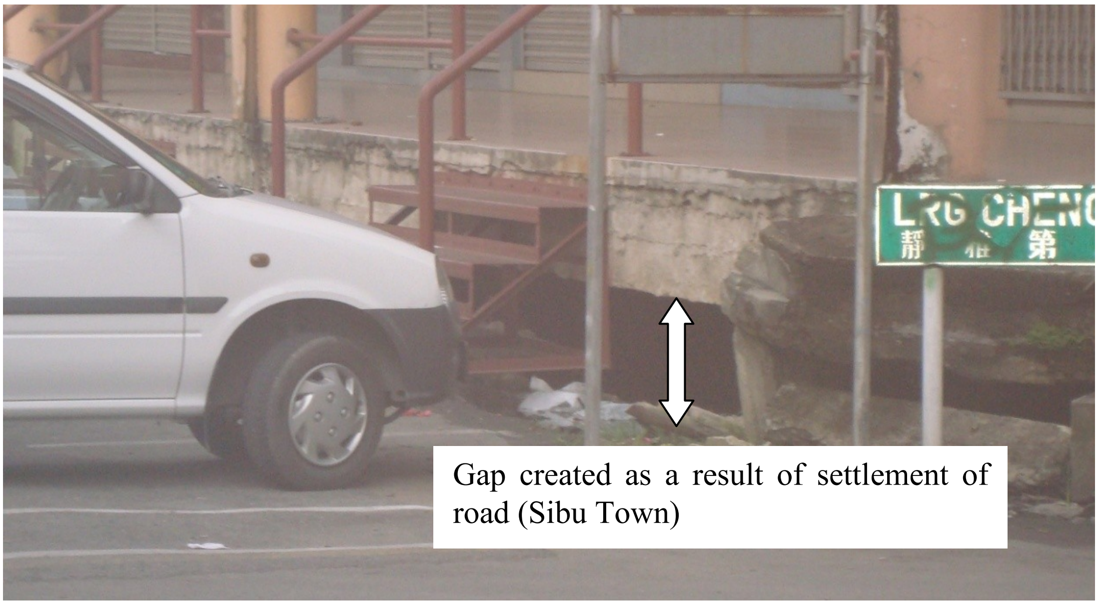


Figure 1.1: Distribution of peat in Sarawak
(http://www.did.sarawak.gov.my/peat/peat_papt/Peatsoil.htm)

Figure 1.1 depicts the distribution of peat in Sarawak. Incidentally the major cities and towns of Sarawak are located along the coastline. The occurrence of peat in the area created engineering problems that hinders the development of the intratown infrastructure as well as the growth of each city and town. With the great distance between each major town, proper land connectivity is necessary for continual economic growth. In the past, there is a tendency to avoid construction on peat due to the time and cost of ground improvement. However, to maintain development in the state, avoidance of problematic soil is no longer an option. This leads to the research and development of various ground improvement techniques.

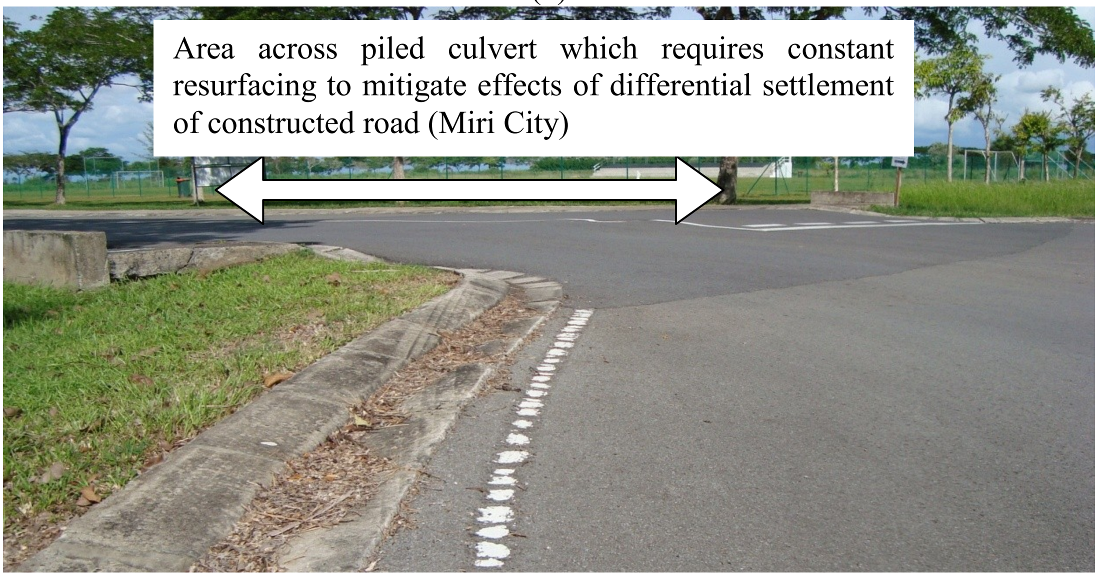
The main problem with peat, as with any other soft soil, would be settlement. Problems with peat and other soft soils can occur as early as the construction stage. The shear strength of the work area may be too low to support the weight of construction machinery. Upon completion of constructed works, the ground could continue to settle, leading to post construction settlement. For constructed works, differential settlement of the ground could pose problems in terms of serviceability and soundness of the completed works.

Figure 1.2(a) and (b) show the post construction settlement problems that occur in the years after completion of a construction. Gaps are created around constructed buildings as the external road and walkway undergo settlement. To allow accessibility to the buildings, extra steps have to be constructed to bridge the gap. Figure 1.2(c) shows the differential settlement occurring between a piled culvert and completed road. As the road settles, the top of the culvert creates an uneven surface on the road. With further settlement, resurfacing of the road is required to mitigate the uneven road surface due to settlement.



(a)

(b)



(c)

Figure 1.2: Post construction settlement problems in (a) Sibu Town; (b) Miri City and (c) completed roads in Miri City

To overcome the problem of settlement, studies on the compression of peat are carried out in order to better understand the compressibility of peat (Wong *et* al. 2008a; 2008b; Duraisamy *et* al. 2007b). Continual research on ground improvement is being carried out to address the problem of settlement while taking into consideration the technical viability, overall cost of the project and the length of time allowable.

Duraisamy *et* al. (2007a) presented several ground improvement techniques for construction on peat. Shallow peat can be excavated and replaced with suitable imported fill material. High cost could be incurred due to imported fill and location of a suitable dumping site for the excavated peat. This replacement method is limited to peat with depth of less than 6m (Duraisamy *et* al. 2007a).

For larger depths of peat, available methods of ground stabilization include deep soil mixing method (Islam and Hashim 2009), installation of cement columns (Kazemian and Huat 2009), and addition of chemical admixtures (Huat *et* al. 2005). Another ground improvement method is the preloading technique where surcharge in the form of temporary fill is placed on top of the peat (Duraisamy *et* al. 2007a). Application of the surcharge results in the consolidation of the peat. The aim of preloading is to allow the peat to settle beyond the expected design life settlement, hence lessening the effects of post construction settlement. With the significant quantity of surcharge material and relatively long surcharge period, prefabricated vertical drains were introduced to reduce the drainage path length and increase rate of consolidation (Indraratna *et* al. 2010).

Recently, researchers and geotechnical engineers have carried out numerous studies on an alternative improvement method, known as electro-osmotic (EO) consolidation. Most studies done showed the effectiveness of this method on consolidation of soft clay. Without the application of surcharge, soft clay that underwent electro-osmotic consolidation achieved the same amount of improvement in shear strength approximately 10 times faster than the time taken for surcharge with vertical drain (Chew *et* al 2004).

1.1.2 Electro-osmosis (EO)

Application of direct current through a saturated, conductive, porous medium results in electrokinetic phenomena. Physicochemical and hydrological changes occur in the medium under direct current application. Major movement processes of different species in the medium are electro-osmosis, electrophoresis, streaming potential and sedimentation potential. Electro-osmosis is the movement of fluid and electrophoresis is the movement of charged particles. Streaming potential is the electrical potential difference generated as water flows and sedimentation potential is the potential difference resulting from movement of charged particles (Acar and Alshawabkeh, 1993).

Electro-osmosis has been widely studied due to its practical aspect where water can be transported in fine-grained medium. When direct current is applied to a saturated medium, an electric field is created between the positively charges electrode (anode) and the negatively charged electrode (cathode). This electric field results in movement of the water in the medium. Positively charged ions move towards the cathode, drawing with them the free water in the medium. At the same time, negatively charged ions are drawn towards the anode. However, as a result of a higher concentration of positively charged ions in comparison to negatively charged ions, the net flow of water is in the direction of the cathode (Mitchell, 1991).

Application of direct current to a soil causes electrolysis reactions at the electrodes. As the soil medium is saturated, oxidation reaction occurs at the anode while reduction reaction occurs at the cathode. These reactions produce H+ and OH- at the anode and cathode respectively. The electrolysis reactions at both anode and cathode can be described as follows

$$2H_2O - 4e^- \rightarrow O_2 \uparrow + 4H^+ (anode)$$

$$4H_2O - 4e^- \rightarrow 2H_2 \uparrow + 4OH^+ (cathode)$$

The formation of these ions generates an acidic front in the vicinity of the anode and an alkaline front surrounding the cathode. Acar *et al*. (1990) has found that pH at anode will drop to below 2 and the pH at cathode will increase to above 12.

The acidic front from anode is moved toward the cathode via mechanisms such as electromigration, electroosmosis or diffusion resulting from chemical gradient formed between the anode and cathode (Alshawabkeh and Acar, 1992). The alkaline front developed at the vicinity of the cathode initially also advances toward the anode via electromigration and diffusion. However, the higher effective ionic mobility of the hydrogen ion causes it to be more dominant in a system where both hydrogen ion (H+) and hydroxide ion(OH-) co-exists. This dominance of H+ will neutralize the alkali front and mask the movement of OH- toward the anode. (Acar and Alshawabkeh, 1993). In soil with high buffer capacity, the change in soil pH might not be significant, as seen in the contaminant removal study in kaolin by Oonnittan *et al*. (2013). In the study, initial pH of kaolin was 5.2 and at the end of the test, pH of the kaolin ranged from 2.8 to 5.8, which is lower than the recorded values by Acar *et al*. (1990).

Electro-osmosis is currently a widely accepted technique for removal of soil contaminant in fine-grained soils. The low hydraulic conductivity of fine-grained soils limits the fluid flow rate required to transport contaminants through the soil for removal. Studies on remediation of clay were carried out by Alshawabkeh *et* al. (1999), Page and Page (2002) and Xu *et al*. (2015).

Using the same concept, studies and trials were carried out to determine further usage of the same technique in dewatering. Using steel mesh as horizontal electrodes, Lockhart and Stickland (1984) designed a field test for dewatering of coal washery tailings pond. Other dewatering applications includes wastewater sludge (Mahmoud *et al*, 2011), waste sludge (Raats *et al*., 2002) as well as tomato paste suspension (Al-Asheh *et al*., 2004).

In the field of engineering, studies were carried out on soil strengthening and stabilization using electro-osmosis. Glendinning *et al*. (2005) constructed a reinforced earth wall using cohesive fill and electrokinetic geosynthetics. Electro-osmosis was used to improve the shear strength of the cohesive fill. Electro-osmotic treatment of clay was also done to improve the load capacity of installed piles (Naggar and Routledge, 2004, Ng *et al*., 2007).

In the stabilization of soil, electro-osmosis flow is the part of electrokinetic phenomena that plays a major role in generating fluid flow (Acar and Alshawabkeh, 1993). Electro-osmotic flow is the movement of fluid due to applied electric potential differences. Positively charged are attracted to the negatively charges cathode, dragging free water toward the cathode. At the cathode, the water is removed and this coupled with no replenishing of water at the anode results in consolidation. In South East Asia, laboratory studies as well as field studies were carried out in soft Bangkok clay (Bergado *et al*. 2000, 2003) and Singapore Marine clay (Chew *et al*. 2004). Similar studies have been done in Canada and UK on clay as well as marine sediment (Shang 1998, Mohamedelhassan and Shang 2002, Barker *et al*. 2004). The studies showed positive results in application of electro-osmotic consolidation as a form of ground stabilization.

In the study of electrokinetics, the effectiveness of electrodes was also investigated. In the past, metallic electrodes were used. However the unprotected electrodes were prone to corrosion in the acidic front of the anode and hence reducing its effective area. To overcome this, electrokinetic geosynthetics (EKG) were developed (Hamir *et al*., 2001). EKG materials are in the form of conductive polymers or composites of conductive and non-conductive materials. For consolidation, filter geosynthetic is also added to electrically conductive composite to provide filtration and drainage function. These are generally similar to prefabricated vertical drains or wick drains.

1.1.3 Potential of EO in Peat and Organic Soil Consolidation

Most of the EO consolidation studies were carried out in clay and few were done in peat or organic soil. Peat has low hydraulic conductivity, similar to fine-grained clays. As field studies on the EO consolidation in clay have been successfully carried out, there is a possibility of introducing EO consolidation as a ground improvement technique in peat. As EO consolidation can be carried out with or without surcharge, the problem of granular fill material can be minimised or eliminated.

Currently, only limited studies on the EO consolidation of peat and organic soil are being carried out. Hence this research is done to study the various factors in EO consolidation. One of the areas of interest is the effect of voltage gradient during EO consolidation of peat. Applied voltage gradient in peat during EO consolidation should be in a range sufficient to generate flow in the peat without resulting in overly high power consumption. Another area of interest would be the effect of electrode configuration on EO consolidation. By using 1D and 2D electrode configurations, the improvement of peat with different electrode configurations can be studied.

1.2 Aim and Objectives

The overall aim of this research focuses on the effects of EO on the consolidation of peat and organic soils. The objectives of the study are as follows:

1. To assess the effect of voltage gradient on electro-osmotic consolidation of peat and organic soil
2. To evaluate the effect of square and hexagon radial electrode configurations on electro-osmotic consolidation of peat
3. To investigate the effect of pumping intervals of drainage well during electro-osmotic consolidation of peat and organic soil
4. To study the improvement of peat and organic soil subjected to polarity reversal during electro-osmotic consolidation

1.3 Layout of Thesis

This thesis comprises of seven chapters. Chapter 1 introduces the background, need for this research on peat and organic soil, aim and objectives of this study. Chapter 2 present the review of relevant literature, introducing the theory of electrokinetic in general and electro-osmosis in particular. This chapter also outlines the parameters and previous studies carried out to evaluate electro-osmotic consolidation. Chapter 3 provides the experimental test plan, including properties of peat and organic soil used in the laboratory tests. This chapter also details the experimental setup and procedures of the laboratory tests. Chapter 4 presents the results obtained from EO consolidation tests with varied voltage gradient. The set of tests include fixed applied voltage gradient, incremental applied voltage gradient and constant current. Analysis and discussion of the results are also presented. Chapter 5 presents the study on radial electrode configuration at different applied voltage gradients. Comparison of the two different radial electrode configuration used in the study is also presented. Chapter 6 reviews the effect of pumping interval and polarity reversal during EO consolidation. Data analysis and discussion of results from the experimental tests are also presented. Chapter 7 presents the summary and conclusions of the major findings of this research. In addition to that, recommendations for further research work are included.

2 Literature Review

2.1 Introduction

In the consolidation of soils, the removal of water from the soil is required in order for the soil to consolidate. In fine-grained soils, electro-osmosis increases water flow in soil under the influence of an electric field. This chapter reviews the factors governing electro-osmosis (EO) flow seen in the quantifying equation for EO flow. The electro-osmotic permeability, voltage gradient and area of flow govern the volume of EO flow. Included in this review is polarity reversal during electro-osmosis which was reported to increase uniformity of shear strength gain between the cathode and anode. The choice of electrode materials is briefly discussed as it affects the efficiency of electro-osmosis. Several cases of field tests on EO consolidation in clay are also presented. The feasibility of electro-osmosis in peat and organic soil is discussed based on previous studies to determine the properties of peat and organic soil conducive to electrokinetics.

2.2 Consolidation of Soft Soils

Soils with highly compressible nature such as peat and clay are often termed as soft soils. The compressible nature of soft soils makes them prone to problems with bearing capacity and settlement. Sites with soft soil have to be improved before commencement of construction works. The low shear strength of soft soils needs significant improvement as its natural bearing capacity is very low and negligible. In the past, developers had the option of passing over sites with soft soil conditions. This was done to avoid post-construction settlement problems as well as higher project costs incurred at the foundation level.

With the current rapid development, the option of avoiding soft soils is no longer possible. In order to utilize sites with soft soils, one of the conventional ground improvement technique used is surcharging (Yee and Ooi, 2010). Imported fill materials were placed on top of the soft soil to provide a sustained static load or surcharge. The surcharge resulted in consolidation of soft soil and allow for primary settlement to take place before construction works began. In projects where time is a constraint, vertical drains were installed to increase drainage and expedite consolidation. Inclusion of vertical drains during surcharge can reduce the surcharge period to four to five months. Surcharging of soft soils is time consuming since filling has to be carried out progressively to avoid bearing failure. Depending on the depth of soft soil to be treated, the amount of imported fill material required for surcharge can be massive. When the thickness of fill is high, it posed a risk of embankment instability. Steps to provide stability to high fills have to be taken. Other problems encountered in the surcharging technique could occur in the availability of suitable fill material as well as proper disposal of fill material after surcharging. In most construction projects, time for ground improvement is a major concern along with the stability of surcharge fill height. These concerns led researchers to study ways to reduce consolidation period as well as reduction in surcharge fill height. One of the possible solutions is electro-osmotic consolidation.

2.3 Electro-osmotic Consolidation of Clay

A study carried out by Lo *et al.* (1991) on soft sensitive clays found a similarity in settlement-time curves between the conventional surcharge consolidation and electro-osmotic consolidation. The coefficient of consolidation was found to increase, an indication that consolidation by electro-osmosis can be achieved at a faster rate than conventional surcharge loading. Bergado *et al.* (2000) also reported similarity in the settlement-time curves for consolidation with vertical drains and electro-osmotic consolidation. Time taken to achieve 90% degree of consolidation using electro-osmosis was 1.2 to 2.2 times faster than consolidation with vertical drains. Magnitude of settlement that occurred in electro-osmotic consolidation was 27 – 101% more than consolidation with vertical drains.

Chew *et al.* (2004) carried out electro-osmotic consolidation on soft Singapore marine clay. Treatment area was 50m x 50m with electrodes spacing of 1.2m. From the field study by Chew *et al*. (2004), it was estimated that electro-osmosis improvement was about 10 times faster than consolidation with vertical drains. Rittirong *et al.* (2008) conducted a field test on soft clayey silt in Kuching, Sarawak. The ground improvement was for widening of the existing access road from 8m-wide to 16m-wide. Treatment area was 560m x 4m on each side of the existing road.

Initial undrained shear strength ranged from 5 to 13kPa. After five days of electro-osmosis treatment, the average undrained shear strength increased to range from 22 to 39kPa. Within a period of five days, the undrained shear strength has increased by three times. The results of electro-osmosis treatment in clay provided a basis for possible application in peat and organic soils. Similar to soft clays, peat areas require ground improvement before it can be utilized. The high water content, low hydraulic permeability and highly compressible nature of peat also require prolonged treatment period using the conventional surcharging method. Hence in recent years, study on the feasibility of electro-osmosis consolidation in peat and organic soils were carried out.

2.4 Feasibility of Electro-osmosis on the Consolidation of Peat and Organic Soil

Studies on electro-osmotic consolidation of soils are mainly carried out in clay or clayey material. This is due to the charges of the ion minerals found in clay which allows for the movement of hydrated ions upon application of electric current. In recent years, researchers have studied the properties of peat and organic soil to investigate their feasibility for electrokinetic technique (Asadi and Huat, 2009; Asadi *et al*., 2009; Asadi *et al*., 2010; Asadi *et al*., 2011a; Asadi *et al*., 2011b). Results of the studies show that organic content in peat is responsible for the electro-osmotic flow rather than the mineral fractions, if any, of the peat. Improvements of peat using combinations of cationic reagent grout and Portland cement with electrokinetic method have also been researched (Hossein *et al*. 2014a; Hossein *et al*. 2014b).

The naturally high moisture content of peat makes it a viable environment for electro-osmotic flow, as a saturated medium is desirable for electrokinetics (Asadi *et al*., 2009). Peat contains high non-crystalline colloids or humus (Huat *et al*., 2014). In peat, due to low mineral or clay fraction, the negative charge phenomenon conducive for electro-osmotic flow is found in the organic matter or humus component of peat. Organic matter has high negative charge (Asadi *et al*., 2011a; Forsberg and Aldén, 1988). The organic content of peat is >75%, meaning that peat has a net negative charge. The net negative charge of peat causes water to move from anode to cathode during application of an electric field.

Movement of hydrated ions under an electric field produces a frictional drag which in turn moves the free water resulting in electro-osmotic flow. The measure of the hydrated ions is known as cation exchange capacity (CEC). The CEC of humus is high in comparison with other colloidal materials such as kaolinite, montmorillonite. Asadi, Huat and Shariatmadari (2009) conducted measurements of CEC at pH 7 and peat natural pH of 5.5 to 6.4 of Malaysian peat. The measured values of CEC range from 36 to 109 meq/100g at pH 7 and 33 to 109 meq/100g for peat natural pH. In the same study, it was found that measurement of CEC at pH 7 resulted in overestimates in measured values. This is due to buffering of organic soils at pH 7 as the charges in the organic soils are pH dependent.

Another factor affecting the viability of electrokinetics in peat and organic soils is the zeta potential (ξ). Zeta potential of the soil is directly related to electro-osmotic permeability and electro-osmotic flow in the soil (Equation 2.2). Zeta potential is the measure of electric potential between the fixed and moving portion of the electrical double layer. Zeta potential is measured by microelectrophoresis using an electrophoresis cell. The velocity of the moving colloids in the electrophoresis cell is proportional to their zeta potential. The direction of moving colloids is indicative of the charge of the colloids. Electro-osmotic flow is in the direction of the cathode when ξ is negative (negative surface charge) and flow is toward the anode when ξ is positive. The range of ξ of organic soils is found to be dependent on soil pH with values of +41 mV at pH 1.91 to -43 mV at pH 11.5 (Asadi *et al*., 2009). Asadi *et al*. (2009) reported that higher natural ξ values were obtained from peat and organic soils with higher organic content. However, the increase of ξ in organic soils is also attributed to the higher mineral fractions in the organic soil. Electro-osmotic flow could be terminated at iso-electric point when ξ is 0 mV. For organic soils, the iso-electric point occurs between pH 2.5 to 3.5. Under natural pH conditions, the values of ξ range from -11.2 to 13mV in peat and -14.2 to -20.8 mV in organic soils (Asadi *et al*., 2009).

The coefficient of electro-osmotic permeability of peat was also investigated. Asadi *et al*., 2010 found that the average coefficient of electroosmotic permeability (k_e) in peat ranged from 1.37 x 10^{-6} to 1.97 x 10^{-6} cm^2Vs^{-1} in fibric peat and 1.72 x 10^{-5} to 2.35 x 10^{-5} cm^2Vs^{-1} in amorphous peat. The coefficient of electro-osmotic permeability reached maximum values after 2 days. After 10 days of testing, the average coefficient of electro-osmotic permeability declined to a minimum. Similar trend in changing magnitudes of coefficient of electro-osmotic permeability was also recorded in kaolinite (Eykholt and Daniel, 1994).

The investigation on the properties of peat and organic soils with regards to the viability of electrokinetics show promising results. The values of CEC, ξ and k_e show that electro-osmotic flow is viable in peat and organic soil. However, the study on peat and organic soils done so far mainly concentrated on the viability of properties of peat and organic soils for electro-osmosis treatment. Most of the tests were done with open-cathode and open-anode condition, where consolidation do not occur. Limited tests have been conducted on the consolidation of peat and organic soils using electro-osmosis treatment. Hence this research aims to study the improvement of peat and organic soil in terms of settlement, water content reduction and strength gain after electro-osmosis treatment.

2.5 Electro-osmotic (EO) Consolidation

Electro-osmosis is constantly being studied as an alternate ground improvement in soft soils. Most of the studies were carried out on clay due to high negative surface charge of clay particles. This section discusses the laboratory test set-up used in previous studies, including electrodes selection.

2.5.1 Laboratory EO Consolidation Test Set-up

There is currently no specific standard on the EO cell set-up, hence previous researchers developed EO consolidation test tanks based on the requirements of their study area. Casagrande (1949) used a simple set-up, allowing for various conditions at the anode and cathode.

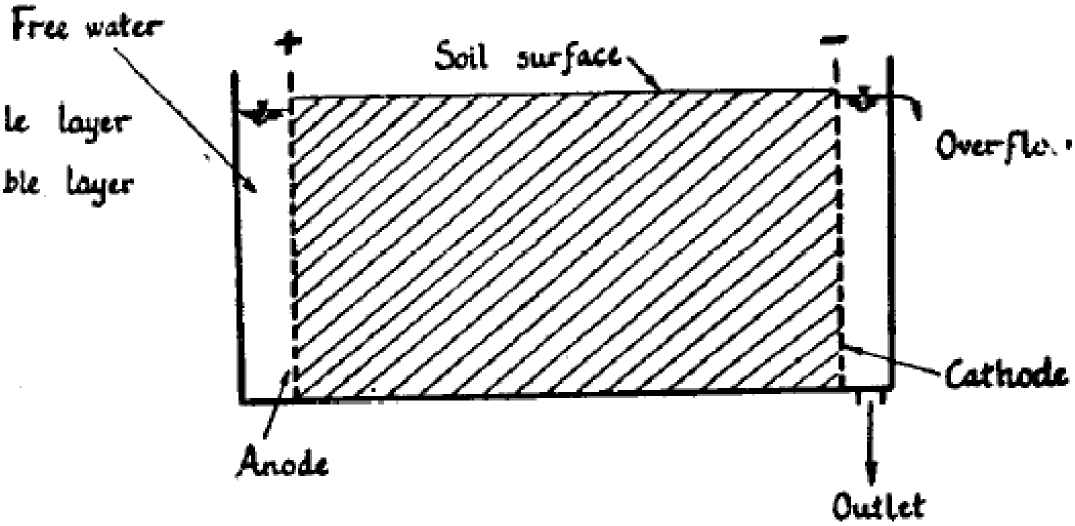


Figure 2.1: Apparatus used for EO flow investigations (Casagrande, 1949)

Figure 2.1 shows a sketch of the apparatus used in Casagrande's (1949) laboratory investigations of EO in clay. Using this apparatus, Casagrande was able to model different conditions at both the electrodes, with conditions such as flooded soil surface, free water at the anode or no access to outside water at the anode. From this set-up, values of osmotic discharge of water and pore pressures were obtained.

Based on the apparatus for EO flow by Casagrande, different cathode and anode conditions can be controlled to get different end results or conditions during application of electro-osmosis. The condition required for consolidation is the *anode closed – cathode opened* condition where the anode has no access to free water and the water collected at the cathode is removed from the system. Flow of water from the anode toward the cathode and its subsequent removal at the cathode causes consolidation to occur. Movement of water away from the anode region generates a negative pore pressure at the anode. Since the main flow of water is toward the cathode, the area surrounding the cathode undergoes little to no consolidation during the EO process.

Under the assumption that total stress in the soil remains unchanged, the difference in pore water pressure between the cathode and anode creates a hydraulic gradient in the soil medium. This hydraulic gradient is the driving force for moving water back from the cathode toward the anode. When the electro-osmotic force driving water toward the cathode is balanced by the hydraulic force pushing water back toward the anode, consolidation subsequently ceases (Mitchell as cited in

Bergado *et al*. 2002). The negative pore pressure developed at a distance x from the anode under a uniform electric field is given by

$$u_e(x) = -\frac{k_e \gamma_w}{k_h} i_e x \quad (2.1)$$

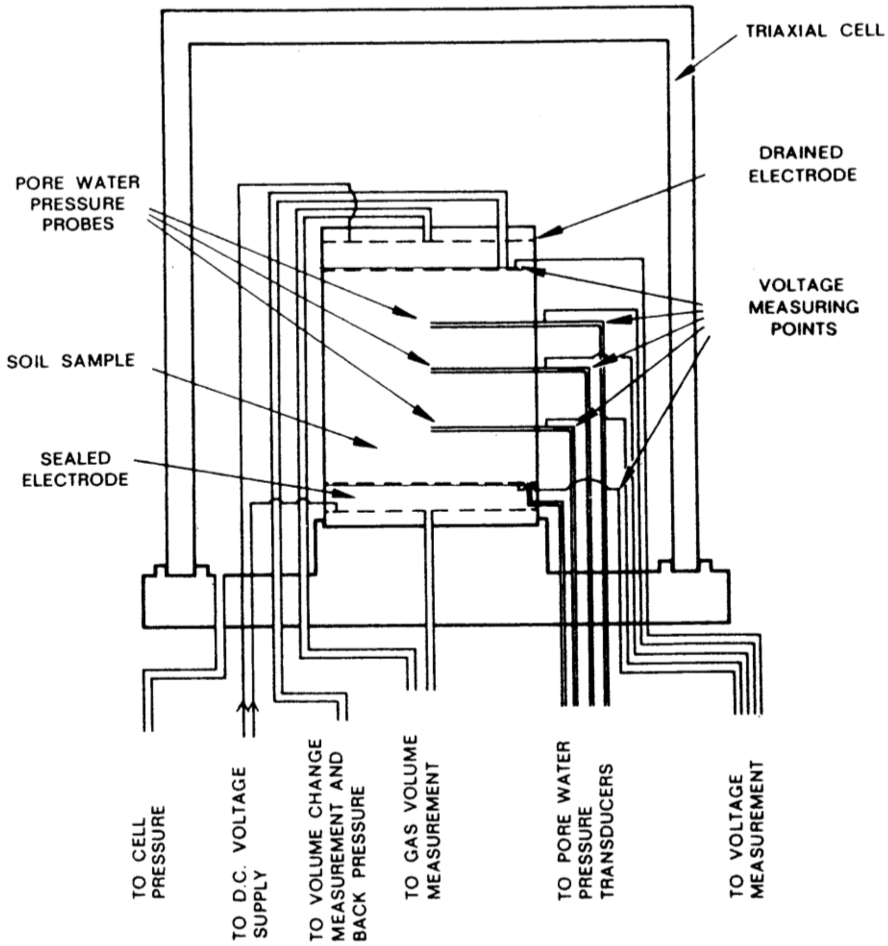


Figure 2.2: Modified triaxial cell for laboratory EO consolidation (Johnston and Butterfield, 1977)

Figure 2.2 shows a modified triaxial cell for laboratory EO consolidation with horizontal electrode placement and horizontal EO flow (Johnston and Butterfield, 1977). The electrodes were place at the top and bottom of the test soil sample. Measuring points were included for voltage measurements, pore water pressure measurements and gas volume measurement. The horizontal electrode and horizontal EO flow set up is more suitable for obtaining coefficients of electro-osmotic permeability.

For field applications of electro-osmosis, it is more practical to have vertical electrode installations with EO flow occurring in the horizontal direction while the settlement occurs in the vertical direction. Hence in this study, the test setup consists of vertical electrodes to allow for EO flow in the horizontal direction. Drainage wells are included for the collection of water and its subsequent removal. Measuring points for settlement, voltage and current during the test duration are also included.

2.5.2 Electrode Materials

Mohamedelhassan and Shang (2001) investigated the effects of three different electrode materials, namely carbon, steel and copper, on the coefficient of electro-osmotic permeability and soil-interface voltage losses in a marine soil. Six pairs of electrodes using different combinations of the three electrode materials were used in the test. Results of the study showed that the coefficient of permeability is independent of electrode material and dependent upon the effective applied voltage.

Hamir *et al*. (2001) investigated the use of electrically conductive geosynthetic (EKG) materials as electrodes in electrokinetic processes. Tests on EO consolidation using EKG electrodes showed similar results to EO consolidation using copper electrodes. The major advantage of EKG material is that it does not undergo corrosion during the electrolysis process, unlike copper and any other metal electrodes.

Metal electrodes tend to corrode during electrolysis, hence reducing the efficiency of the overall system. Metal electrodes at great lengths and large quantities can be costly as well. EKG electrodes provided an alternative to usage of corrode metal electrodes during EO process.

2.6 Electro-osmosis (EO) Flow

Casagrande (1949) initially introduced the theory of electro-osmotic flow using the improved Helmholtz equation, which over the years evolved further into the widely applied Helmholtz-Smoluchowski Theory. This theory is modelled on fluid flow through a capillary under a voltage gradient.

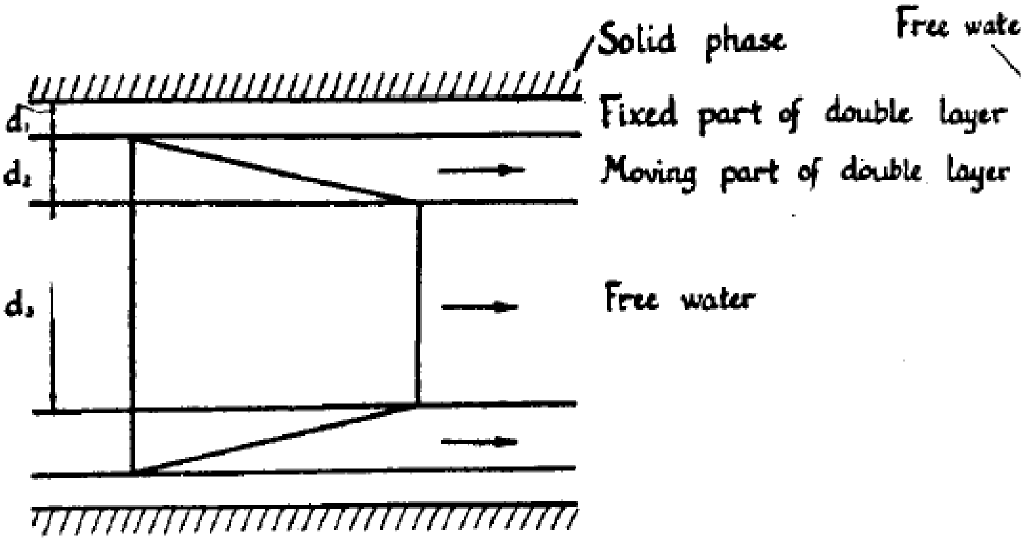


Figure 2.3: Electro-osmotic flow in capillaries showing double layers (Casangrande, 1949)

In Figure 2.3, the walls of the capillary are similar to the negatively charge surface of the solid particles. The fluid in the capillary is divided into three layers, with the third layer being the free flowing fluid at the centre of the capillary. The other two layers make up the double layer, where there is a fixed part adjacent to the capillary wall and a moving part adjacent to the free flowing fluid. Using this concept, the Helmholtz-Smoluchowski Theory is used to quantify EO flow, Q_e, by

$$Q_e = k_e i_e A \qquad (2.2)$$

where A is the cross-sectional area in the direction of flow, i_e is the applied voltage gradient over length between electrodes and k_e is the electro-osmotic permeability which is given by

$$k_e = \left(\frac{\xi D}{\eta}\right) n \qquad (2.3)$$

where ξ is the zeta potential or the electrokinetic potential difference between the fixed part and the moving part of the double layer, D is the dielectric constant, η is the viscosity of the liquid and n is the porosity of the soil. The EO flow equation is similar to Darcy's law:

$$Q_h = k_h i_h A \qquad (2.4)$$

where k_h is the hydraulic conductivity and i_h is the hydraulic gradient. Comparing these two equations, it can be seen that EO flow is dependent on electro-osmotic permeability instead of hydraulic conductivity in Darcy's law. This means that pore size has no effect on the fluid flow in an electrically charged system and EO flow can be induced in fine-grained soils.

By assuming that the Darcian flow and EO flow rates are equal, $k_h\ i_h = k_e\ i_e$, the comparison of gradients required for flow can be expressed as

$$i_h = \frac{k_e}{k_h} i_e \qquad (2.5)$$

From this equation it can be seen that only a small hydraulic gradient is required for movement of water in cases where k_h is much higher than k_e, for example flow in sand. However, in fine-grained soils, k_h is lower than k_e, hence a large hydraulic gradient is required to move water hydraulically. Introduction of a voltage gradient in fine-grained soils can be more effective in inducing water movement. Typical values of k_e reported previously are 5×10^{-9} $m^2/s/V$ (Casagrande, 1949), ranging between 10^{-9} to 10^{-8} $m^2/s/V$ (Mitchell, 1991) and 2×10^{-10} $m^2/V.s$ (Lo *et al.*, 1991a). Mitchell (1991) also stated that values of k_e typically lie in the same order of magnitude for most soil types. However, the efficiency of EO flow can be affected by factors such as desiccation of soil, increased soil resistance and voltage drops.

2.7 Factors Influencing Electro-osmotic Consolidation

This section reviews the factors influencing electro-osmotic consolidation that would be investigated in this study. The first factor is voltage gradient based on electro-osmosis (EO) flow equation (Equation 2.1). Current transmitted through the soil medium is also a factor related to voltage. The electrode configuration during electro-osmosis governs the effective area of treatment. Polarity reversal of electrodes during electro-osmosis in clay was introduced to increase the uniformity of strength gain between electrodes.

2.7.1 Voltage Gradient

Casagrande (1949) suggested an applied voltage gradient of less than 50V/m to prevent heating of soil and subsequent energy loss. Table 2.1 lists some of the voltage gradients used in previous laboratory studies. In the study carried out by Casagrande, a wide range of voltage gradient was used with voltages ranging from 10 to 1200V/m. As the studies on electro-osmosis progressed through the years, the practical aspect for its application came into consideration. Johnston and Butterfield (1977) stated that voltage gradients higher than 100V/m were normally not considered for field applications. The laboratory studies by Yeung & Mitchell (1993), Bergado *et al*. (2000), Mohamedelhassan & Shang (2001) and Kaniraj *et al*. (2011) showed a narrower range of voltage gradients with lower magnitudes.

Table 2.1: Applied voltage gradients in previous studies

Voltage gradient, V/m	Scale of study	Soil Type	
10 ~ 1200	Laboratory	Clay	Casagrande, 1949
100	Laboratory	Clay	Yeung and Mitchell, 1993
60, 80 & 120	Laboratory	Clay	Bergado *et al*., 2000
16 ~ 60	Laboratory	Clay	Mohamedelhassan & Shang, 2001
80 ~ 180	Laboratory	Peat	Kaniraj *et al*., 2011

In the field study of electro-osmosis treatment of soft clay by Kuma (2005), it was found that voltage gradient of 50 to 100V/m was effective for EO treatment under field conditions. Laboratory tests carried out in the same study also indicated effective voltage gradient of the same range. No significant settlement was observed in the field test due to an 18m sand fill and a small treatment area compared to the depth of treatment. However, in the same study, Kuma (2005) found that field vane shear tests showed that the improvement of soft clay with electro-osmosis is about 10 times faster than treatment with vertical drains.

Voltage gradient chosen for EO consolidation should be within a range suitable for the soil medium. Application of overly high voltage gradient shows no further benefits to the improvement of soil and could be a cause of high operating costs (Shang, Lo and Huang, 1996). With the limited literature on EO in peat, the voltage gradient chosen for this study is based on 100V/m. To study the effects of voltage gradient in peat, a lower voltage gradient of 80V/m and a higher voltage gradient of 120V/m are included in this research.

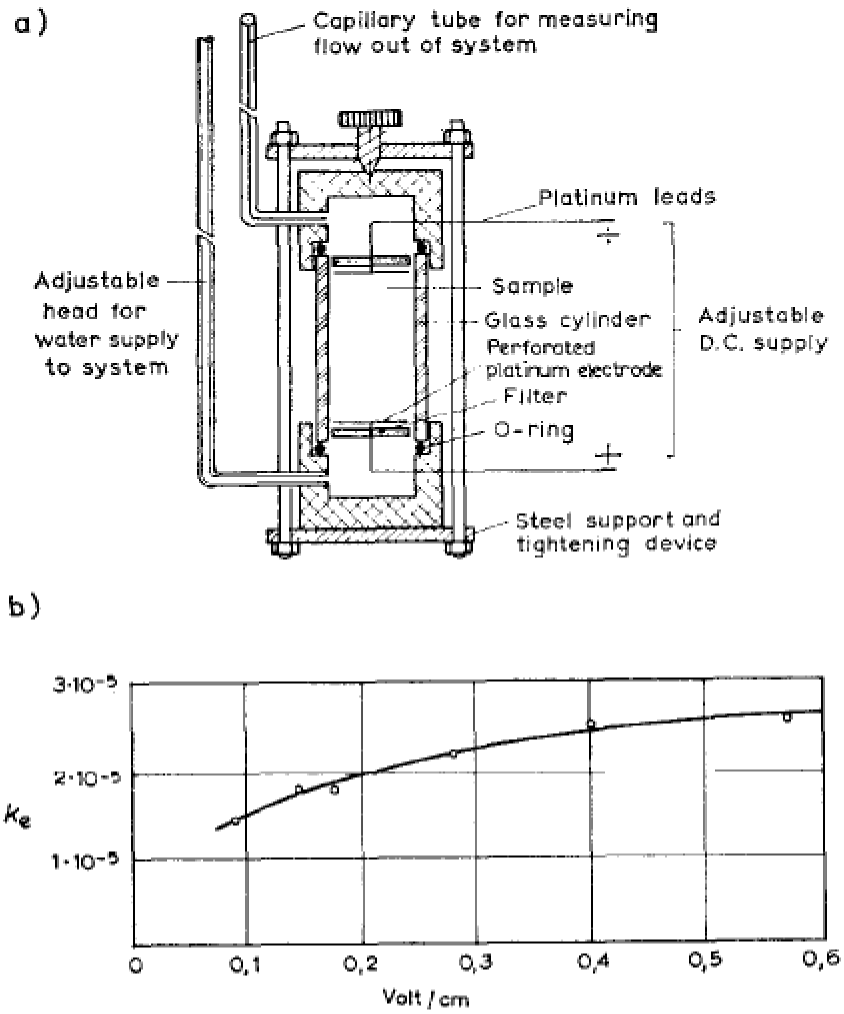


Figure 2.4: (a) Apparatus for determination of k_e, (b) Results of determination of k_e (Bjerrum *et al.*, 1967)

Figure 2.4 shows the results of the laboratory tests carried out to determine the electro-osmotic permeability, k_e, before in situ application of electroosmosis to strengthen an excavation is shown in (Bjerrum *et al.*, 1967). This was to obtain the voltage gradient required to remove the predetermined volume of water needed to achieve increase in shear strength in assumed treatment time of 30 days. According to Equation 2.1, voltage gradient is the influencing factor of the volume of flow during EO. Different voltage gradients were applied to a soil sample taken from the excavation site during determination of k_e. It was found that at lower voltage gradients, the measured values of k_e were lower too. While with the increase in voltage gradient, the measured values of k_e showed increase. However, they also discovered that k_e seemed to converge at 2.8×10^{-9} $m^2/s/V$ with higher voltage gradients. This implies that although k_e increases with increased voltage gradient, there might be a possible maximum k_e value where further increase of voltage gradient might not result in further increase of k_e.

In a later study by Mohamedelhassan and Shang (2001), the effects of current intermittence and electrode materials were investigated. Different coupling of anode-cathode using carbon, steel and copper electrode materials were used. By varying the applied voltage, the authors evaluated the effects of applied voltage on soil-electrode voltage losses. The authors concluded that after taking into consideration the soil-electrode voltage losses, the coefficient of permeability is a function of the effective applied voltage. Varying the applied voltage yielded a conclusion of an apparent limiting higher voltage when the coefficient of electro-osmotic permeability no longer increases with the increase in applied voltage. In the same study, the authors also found that the coefficient of electro-osmotic permeability decreased with time and this change is attributed to the change in zeta potential and decreased of pH at the anode.

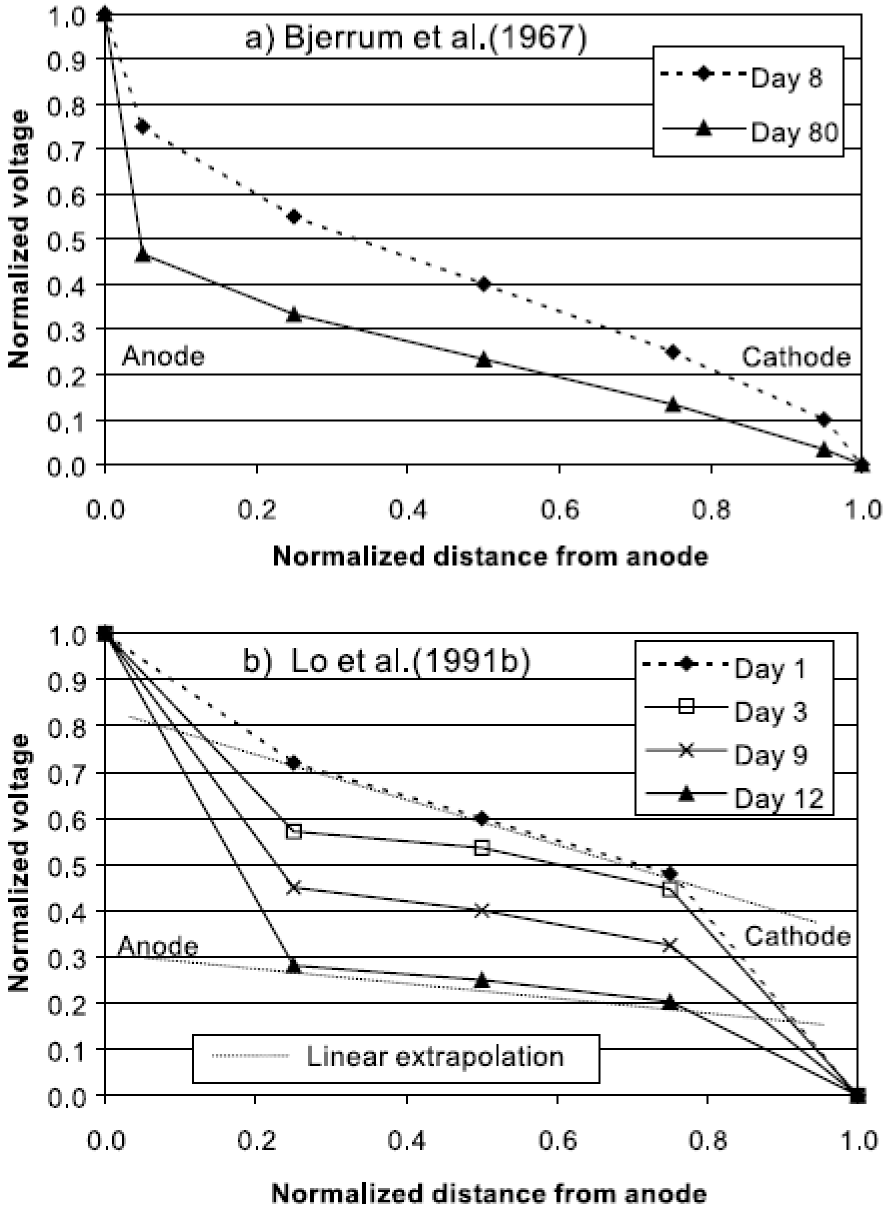


Figure 2.5: Normalized voltage distribution between electrodes versus normalized distance from the anode (Lefebvre and Burnotte, 2002)

Figure 2.5 captures the normalized voltage distribution between electrodes presented by Lefebvre and Burnotte (2002) modelled on field studies done by Bjerrum *et al.* (1967) and Lo *et al.* (1991) respectively. From the graphs, Lefebvre and Burnotte discovered the similarities in voltage distribution between the two different field tests. It was found that the losses were located mainly near the electrodes, with the recorded loss of voltage as high as 70% at the anode and an overall loss of 85% at the electrodes (Lo *et al.* 1991). This means that less than 15% of the applied voltage gradient was effectively transmitted to the soil. In graphical terms the effective applied voltage gradient is seen as the middle region of the graph.

The loss of effective voltage gradient is attributed to the resistivity of the soil-electrode contact. In the same research, they also found that vertical cracks in the soil interfered with the EO consolidation process even in chemically treated soil conditions.

Another variation to fixed voltage gradient during EO consolidation is constant electric current. One such test was carried out by Yukawa *et al.* (1976). In their study, constant current was used in the dewatering of compressible sludge. The authors found that the flow rate and volume of water during dewatering is proportional to the applied electric current. In the cases with fixed voltage gradient, the current transmitted through the soil gradually decreases with time. However with constant current, the current transmitted through the soil medium is kept constant by adjusting the applied voltage. The effects of constant current in organic soil and peat have not been studied.

Voltage gradient chosen for EO consolidation should be within a range suitable for the soil medium. Application of overly high voltage gradient shows no further benefits to the improvement of soil and could be a cause of high operating costs (Shang *et al.*, 1996). The voltage gradients chosen for this study is 80V/m, 100V/m and 120V/m. A set of EO tests with constant current is carried out in organic soil to study the effect of constant current. The constant current values to be used are chosen based on the measured current obtained in tests with fixed voltage gradient.

2.7.2 Electrode Configuration (1D and 2D)

Another concern in electro-osmosis is the electric field area relating to the electrode configuration and electrode spacing. Past study by Schultz (1997) focused on the optimum condition for one dimensional (1D) electro-osmotic flow, taking into consideration electrode spacing, time and energy requirement. Schultz also provided an economic modelling of the electro-osmotic treatment.

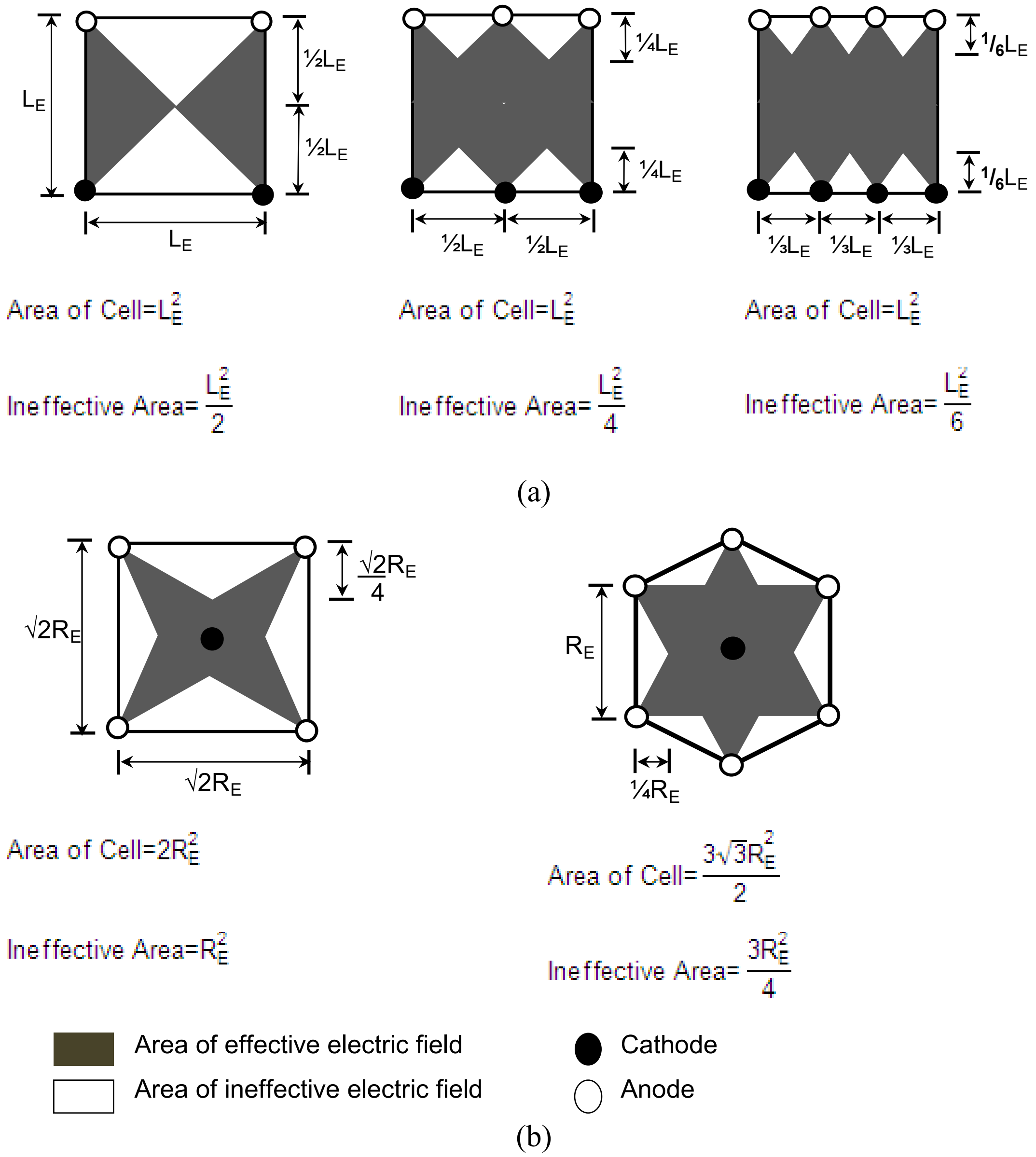


Figure 2.6: Approximate evaluation of ineffective areas for (a) 1D and (b) 2D electrode configurations (after Alshawabkeh *et al.*, 1999)

Alshawabkeh *et al.* (1999) evaluated the application of one-dimensional (1D) and two-dimensional (2D) contaminant transport by electroosmosis. Figure 2.6 shows the different 1D and 2D electrode configurations and their respective effective area of treatment. By comparison, a radial electrode configuration has a smaller ineffective area. The study was limited to the theoretical ineffective areas of two radial electrode configurations, namely the 2D square configuration and the hexagonal configuration.

Glendinning *et al.* (2008) carried out a field trial to dewater sewage sludge using electrokinetics. A prototype ePVD consisting of a central perforated plastic tube encased in geotextile filter and coated with conducting elements was developed for the trial. Trial tests were carried out in two skips with dimensions of 3.7m (L) x 1.8m (W) x 1.6m (D). The electrodes were installed in a rectangular grid array for one skip and a hexagonal array with a central cathode surrounded by six anodes in the other skip. Voltage applied to both skips was 30V with intermittence set at a ratio of 2:1. In the trial, it was found that the hexagonal array resulted in increased volume reduction thus shortening the treatment duration required to achieve 30% volume reduction. With the shorter treatment duration, the overall power consumption is also lower. In the skip with hexagonal array, fewer electrodes were needed compared to that of the rectangular grid array. Better results of the hexagonal array were attributed to a probable combination of several factors with the more important factor being the electrical field shape.

Sahib and Vinod (2010) investigated the effects of different electrode configurations for electro-osmosis. The study was conducted with one rectangular configuration and two tetrahedral configurations. The rectangular configuration was made up of two anodes and two cathodes spaced at 10cm apart. The tetrahedral configuration was arranged with an electrode in the centre and three other electrodes surrounding it. The difference between the two sets of tetrahedral configuration is the polarity of the central electrode. In one test, the central electrode is the anode while the surrounding electrodes are cathodes. In the other test with tetrahedral configuration, the central electrode is the cathode and the surrounding electrodes are anodes. From the tests carried out, it was found that the tetrahedral configuration with the cathode in the centre resulted in strength gain of 76% and the tetrahedral configuration with the anode in the centre resulted in higher water drainage of 33%.

Hu and Wu (2014) conducted numerical modelling of electro-osmotic consolidation in clay using finite-element method to simulate the electro-osmotic consolidation and soil displacement. The numerical study was carried out on three electrode configurations, namely the 1D square configuration and the 2D square and hexagonal configurations. In the numerical study, the authors found that the 2D hexagonal configuration resulted in the highest ratio of average surface settlement to depth. The same hexagonal configuration also showed the lowest ratio of differential settlement to depth. This is in agreement to the theoretical evaluation carried out by Alshawabkeh *et al*. (1999). Few experimental studies were carried out using the 2D electrode configurations.

The use of a radial electrode configuration in array formation in field condition could create a larger effective electric field between electrodes. The ineffective area between electrodes could be reduced with a radial electrode configuration. Reduction of ineffective electric field areas could lead to improvement in a larger soil area, hence minimising areas with lower improvement.

2.7.3 Polarity Reversal

In EO consolidation, due to flow of water from anode to cathode, the cathode region normally registers lower shear strength gain in comparison to the anode region. To try and overcome this shortcoming of the process, polarity reversal is introduced where the polarity of the electrodes are reversed during EO consolidation.

One such case is recorded by Lo *et al.* (1991a) in their study of electro-osmotic strengthening of Wallaceburg clay and Champlain Sea clay. One test was maintained as normal polarity while polarity reversal was carried out in another test. Results of the tests showed that the clay treated with electrode-reversal technique exhibited fairly uniform shear strength throughout the clay. On the other hand, the results of the maintained normal polarity test showed only slight improvement of shear strength at the anode and no noticeable change in shear strength at the cathode.

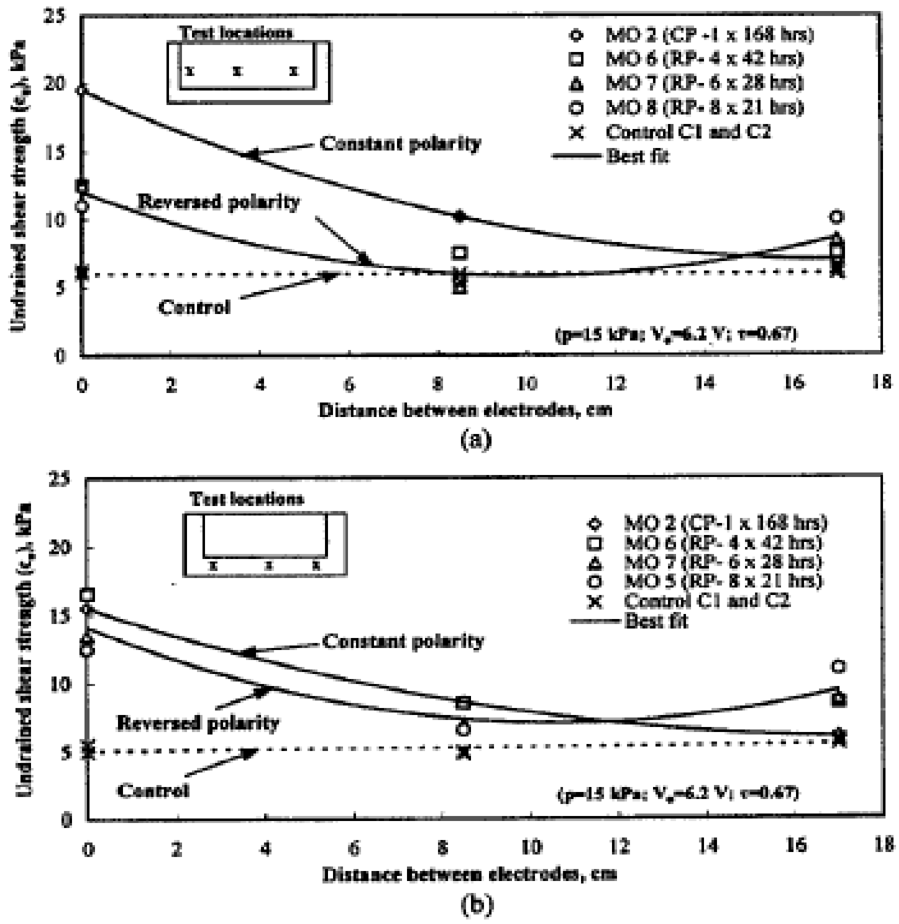


Figure 2.7: Distribution of undrained shear strength across soil sample after EK treatment: (a) adjacent to steel plate and (b) beneath the steel plate (Micic *et al.*, 2001)

Another case study on polarity reversal was done by Micic *et al.*, (2001) on soft marine clay. Figure 2.7 above shows the distribution of undrained strength in the soil sample after treatment with polarity reversal. Earlier tests in the same series without polarity reversal showed higher increase in strength at the anode and lower strength gain in the rest of the soil sample. By reversing polarity of the electrodes during treatment, a more uniform strength gain albeit a lower strength increase at the anode is seen throughout the soil sample. However, periodically reversing polarity of the electrodes saw a lower dewatering effect in the soil sample as water was driven to the centre of the soil at each reversal.

Lo *et al*. (1991b) undertook a field test in soft sensitive clay at a Gloucester test fill site using copper electrodes. Settlement, shear strength and voltage distribution were measured during the study. They reported that there was a similarity in settlement-time curves between conventional mechanical consolidation and EO consolidation. The coefficient of consolidation was found to increase from

0.45m^2/year to a maximum of 18.1m^2/year after EO strengthening, indicating that consolidation by EO can be achieved at a faster rate than conventional mechanical loading. Results of the field vane shear tests showed improvement of 50% in shear strength over the test duration of 32 days. Polarity reversal employed during the field test eliminated low strength improvement at the cathode region and observed settlement was 50mm with differential settlement of ± 20%. Vane shear tests carried out 10 months after completion of EO treatment showed to reduction in the improved shear strength.

In spite of the lower shear strength gain in laboratory tests, field test results have shown shear strength improvement at the cathode regions. Polarity reversal in peat has not been investigated.

2.8 Chapter Summary

The review on past studies shows that electroosmosis is a viable method of consolidation in clays. Relatively little research is done on peat, which is another compressible problematic soil. The introduction of electrically conductive geosynthetic (EKG) materials presented an advantage over conventional metallic electrodes. Electro-osmotic flow and physico-chemical changes in the soil during application of direct current contribute to consolidation and strengthening of soft soils. The arrangement of electrodes is directly linked to the effective area of treatment in soils. A radial electrode configuration minimises the ineffective areas and enhances the EO process. Thus, this study focuses on the effects of electroosmosis consolidation in peat and organic soil, including the influencing factors of EO process which are voltage gradient, current and polarity reversal.

3 Materials and Methodology

3.1 Introduction

This chapter presents the methodology of the test plans, test samples and experimental setup designed to achieve the research objectives. The main aim of this research is to study the effects of electro-osmotic (EO) consolidation on peat and organic soil. Using a small scale and a large scale laboratory experiment setup, EO consolidation was carried out to investigate settlement, water removal and shear strength improvement in peat and organic soil. This study was limited to laboratory studies due to limited resources in terms of available site and funding for a field test.

3.2 Experiment Test Plans

The first segment of the laboratory tests examines the effect of electro-osmosis (EO) in peat and organic soil under different voltage applications and variations. In this set of tests, the effect of fixed applied voltage gradient, namely 80V/m, 100V/m and 120V/m, on peat was studied using both the small scale and large scale experimental setup. This allows for observations of any variation in results between the small scale and large scale laboratory tests. Incremental applied voltage gradient tests were conducted in peat and organic soil using the small scale test setup. For the incremental voltage gradient tests, initial voltage gradient was 10V/m. Stepped increment of 10V/m per day was done for the 8-day test duration. The final applied voltage gradient was 80V/m. Further to that, application of fixed current of 10mA and 20mA was carried out on EO consolidation of organic soil.

The second segment of laboratory tests is concentrated on the large scale test setup using peat samples. The objective of this segment is to investigate the effects of radial electrode configuration on EO consolidation. Two radial electrode configurations, namely the square and hexagon electrode configurations were chosen for the study. The large scale laboratory test setup incorporates a circular test tank to enable study to be carried out in a radial environment compared to the planar environment of the small scale rectangular test tank. The large test tank is also designed in an attempt to observe the effects of electro-osmosis with depth and a larger treatment volume. The laboratory tests were carried out at fixed voltage gradients of 80V/m, 100V/m and 120V/m respectively. Comparison of results was done between the two different radial electrode configurations. Comparison of results between different applied voltage gradient for the same radial electrode configuration was also done.

The third segment of the experimental study was done to evaluate the effects of drainage well pumping intervals on the overall water removal during EO consolidation in peat and organic soil. Pumping intervals chosen are 3hr, 6hr and 24hr. Polarity reversal during EO consolidation was also carried out in this segment of test. Polarity reversal tests were done to examine the uniformity of moisture content reduction and shear strength gain in the test sample upon completion of EO consolidation. Polarity reversal was done at 8hr, 12hr and 24hr for organic soil. In the test with peat, polarity reversal was done at 24hr intervals. In this segment of tests, the small scale rectangular test tank was used.

The summary of the laboratory test plans are summarized in Table 3.1, Table 3.2 and Table 3.3. The soil sample characteristics, setup of the small scale and large scale laboratory tests, sample preparation and test plans are explained further in the following sections.

Table 3.1: Test plan for varied applied voltage gradient

Test Series	Test ID	Soil Sample	Electrode Configuration	Voltage Gradient (V/m)	Duration (Days)	Initial Moisture Content (%)	Initial Undrained Shear Strength (kPa)
1	1A/80/3/M	Peat (M)	1-1	80	8	592	1.71
	1A/100/3/M	Peat (M)	1-1	100	8	549	0.93
	1A/120/3/M	Peat (M)	1-1	120	8	564	1.99
2	G2/80/8/M	Peat (M)	Grid	80	8	394	1.58
	G2/100/16/M	Peat (M)	Grid	100	16	243	2.38
	G2/120/12/M	Peat (M)	Grid	120	12	337	3.05
3	Control/12/O	Organic soil	N/A	0	8	302	0.92
	2A/80/3/O	Organic soil	2-1	80	8	306	1.19
	2A/Incr/3/O	Organic soil	2-1	10~80	8	287	0.92
4	Control/12/S	Peat (S)	N/A	0	8	663	0.92
	2A/80/3/S	Peat (S)	2-1	80	8	654	1.05
	2A/Incr/3/S	Peat (S)	2-1	10~80	8	628	1.19
5	2A/10/3/O	Organic soil	2-1	10mA	8	308	1.19
	2A/20/3/O	Organic soil	2-1	20mA	8	311	1.19

Table 3.2: Test plan for 2D radial electrode configuration

Test Series	Test ID	Soil Sample	Electrode Configuration	Voltage Gradient (V/m)	Duration (Days)	Initial Moisture Content (%)	Initial Undrained Shear Strength (kPa)
6	R4/80/8/M	Peat (M)	Square	80	8	516	1.58
	R6/80/8/M	Peat (M)	Hexagon	80	8	351	4.19
7	R4/100/16/M	Peat (M)	Square	100	16	354	1.85
	R6/100/16/M	Peat (M)	Hexagon	100	16	289	1.71
8	R4/120/12/M	Peat (M)	Square	120	12	297	1.33
	R6/120/12/M	Peat (M)	Hexagon	120	12	284	1.72

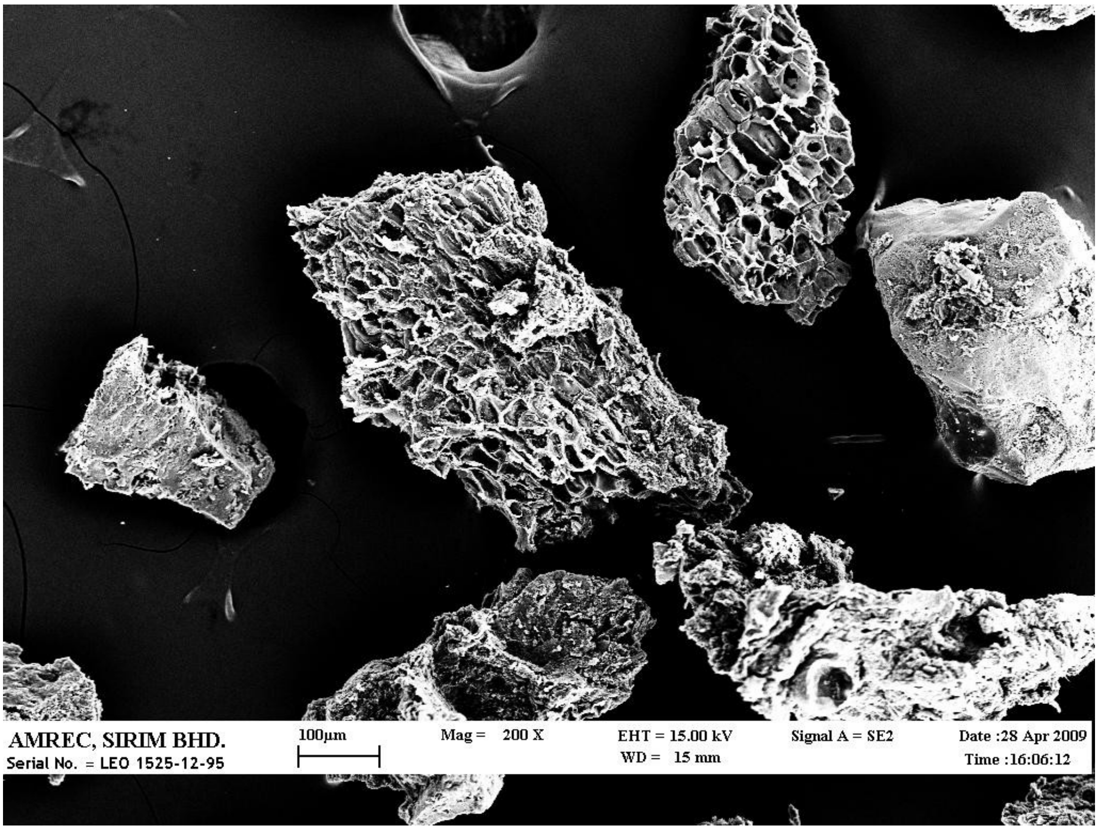
Table 3.3: Test plan for varied pumping interval and polarity reversal

Test Series	Test ID	Soil Sample	Electrode Configuration	Voltage Gradient (V/m)	Duration (Days)	Initial Moisture Content (%)	Initial Undrained Shear Strength (kPa)	Polarity Reversal Interval (hr)
9	Control/12/O	Organic soil	N/A	0	8	221	2.12	
	2A/80/3/O	Organic soil	2-1	80	8	221	1.99	-
	2A/80/6/O	Organic soil	2-1	80	8	219	2.65	-
	2A/80/24/O	Organic soil	2-1	80	8	239	2.12	-
10	Control/12/S	Peat (S)	N/A	0	8	663	0.92	-
	2A/80/3/S	Peat (S)	2-1	80	8	654	1.05	-
	2A/80/6/S	Peat (S)	2-1	80	8	667	1.60	
11	2A/80/3/O/8R	Organic soil	2-1	80	8	254	0.92	8
	2A/80/3/O/12R	Organic soil	2-1	80	8	249	1.19	12
	2A/80/3/O/24R	Organic soil	2-1	80	8	254	0.92	24
12	2A/40/3/S/NR	Peat (S)	2-1	40	8	641	1.06	No reversal
	2A/40/3/S/24R	Peat (S)	2-1	40	8	650	1.06	24

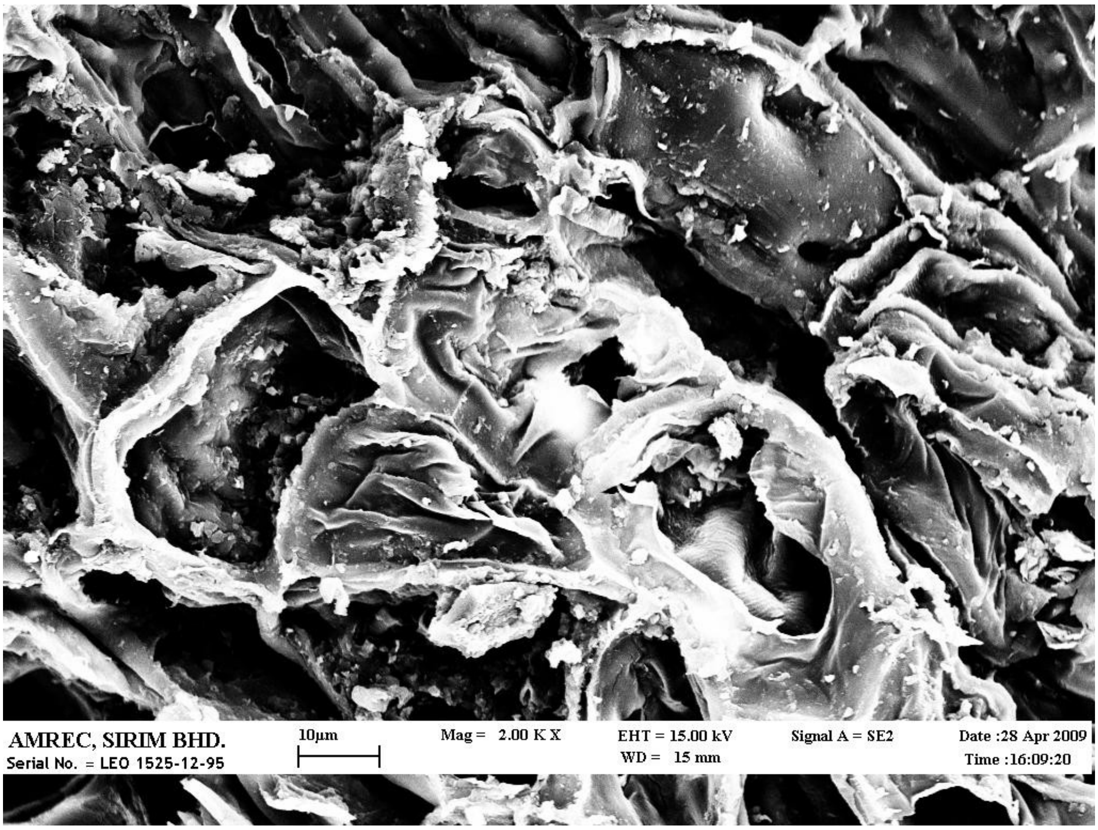
3.3 Test Materials

3.3.1 Soil sample

Peat used in the experiments was collected from two different locations in the state of Sarawak, namely Similajau (denoted as S) and Miri (denotated as M). Peat was sourced from two locations as there was difficulty in procuring large volume of peat from a single site. There was also limited suitable storage space available. In order to retain the natural water content of peat, the sourced peat was sealed in large plastic bags. The bags of peat were then stored in the concrete curing room, where the environment was cool and enclosed. This was done to prevent moisture loss of the peat. With the availability of peat from two different sources, this would enable the study of electro-osmosis of peat from different locations. The organic soil used in this research was collected from Sibu (denoted as O). Properties of the soils were carried out in the laboratory according to British Standards and ASTM.

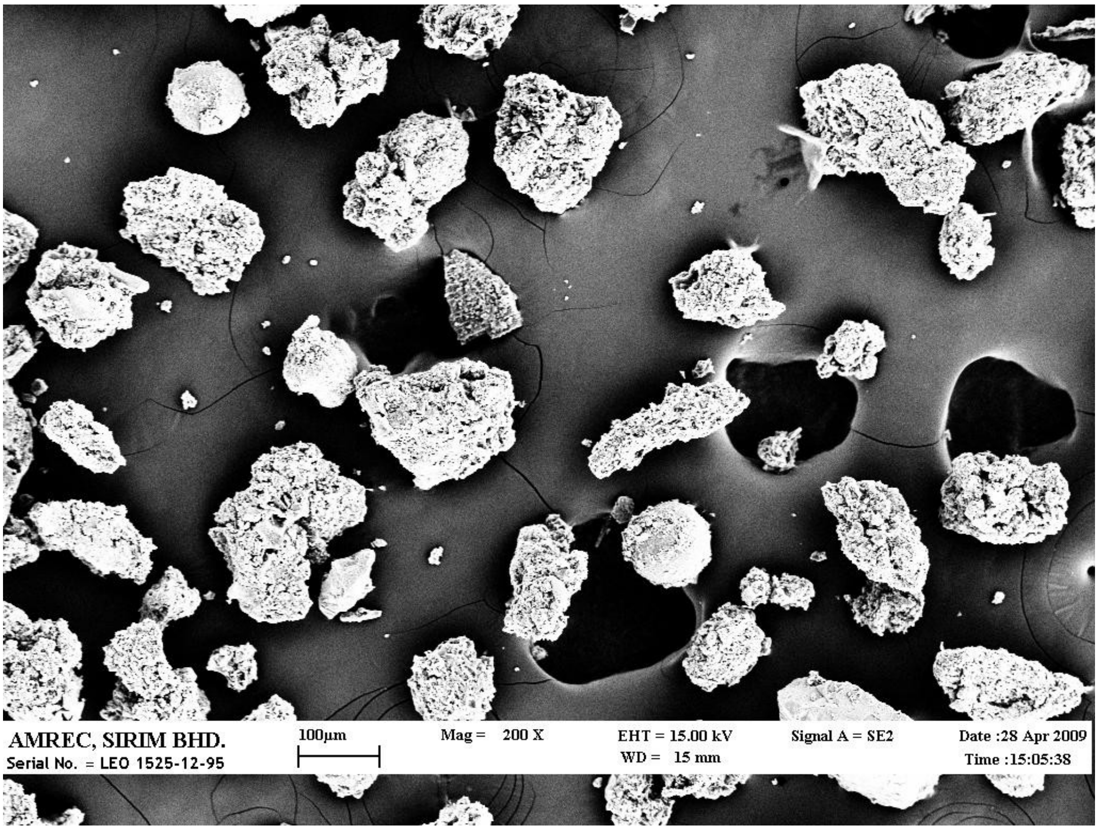


(a)

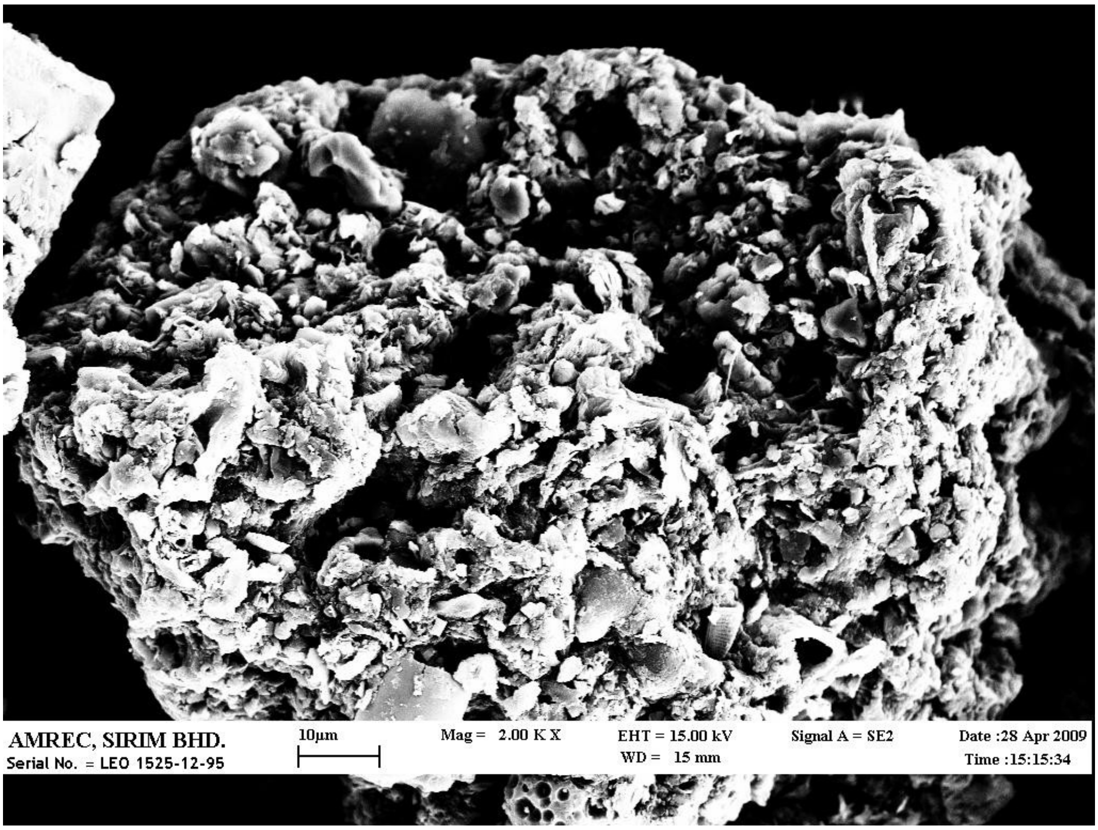


(b)

Figure 3.1: Scanning electron microscope image of peat from Similajau at (a) 200x magnification; (b) 2000x magnification



(a)



(b)

Figure 3.2: Scanning electron microscope image of organic soil from Sibu at (a) 200x magnification; (b) 2000x magnification

Figure 3.1(a) and (b) show the SEM images of peat from Similajau at 200x and 2000x magnification respectively. At lower magnification, the image shows the fibrous nature of peat. At higher magnification, large pore spaces are highly visible. Figure 3.2(a) and (b) show the SEM images of organic soil from Sibu at 200x and 2000x magnification respectively. The lower magnification shows the granular structure of the soil. The higher magnification image indicates that there are less pore spaces in organic soil when compared to peat.

The determination of the soil natural content was done using the moisture content test (BS 1377:1990). In each test, a small sample of soil was dried at 105°C for 24 hours. The moisture content was calculated as the weight of water divided by the weight of oven-dried soil and presented as a percentage.

The organic content of soil was determined by the ash content as a percentage of oven-dried soil mass (ASTM D 2974). Soil sample to be tested was dried at 105°C for 24 hours. The oven-dried soil was transferred into a porcelain dish and heated in a muffle furnace at 440°C for 6 hours. The ash content was calculated as a percentage of weight of ash divided by weight of oven-dried sample. The organic matter was obtained as follows:

$$\text{Organic matter, \%} = 100 - \text{ash content} \quad \textbf{(3.1)}$$

The Atterberg limits were determined in accordance with BSI 1377-2: 1990. The cone penetrometer method was used to determine the liquid limit of the soil samples. Soil samples were mixed from its natural state into a paste and placed into a metal cup. With the soil-filled metal cup place directly under the cone, the cone was released for 5s to allow for penetration into the soil. The depth of penetration was recorded for at least three more times at different moisture content. The liquid limit of the soil was the moisture content of soil at 20mm cone penetration. To obtain the plastic limit of soil, soil samples were rolled into threads of 3mm diameter. The plastic limit was the moisture content of the soil at the point when the soil thread started to crumble at 3mm diameter.

Table 3.4 shows the properties of the soils used in this study. The peat sourced from Similajau (S) and Miri (M) show high natural water content > 500%. Both peat from Similajau (S) and Miri (M) show high organic contents of 95% and above. The organic soil collected from Sibu (O) has organic content ranging from 48 to 50%. The Atterberg limits of the peat and organic soil are also shown in Table 3.4.

Table 3.4: Properties of soils used in laboratory scale experiments

	Peat (S)	Peat (M)	Organic Soil (O)
Natural water content, w_m (%)	550 - 691	609 – 906	80 - 95†
Organic content, N (%)	96	95 – 99	48 - 50
Atterberg limits			
Liquid limit, w_l (%)	323	336 – 359	245
Plastic limit, w_p (%)	244	N/A	155
Plasticity index, PI (%)	79	N/A	90

† With the time lapse between collection and transport to the lab, organic soil sample underwent drying. Results of moisture content presented are not the in-situ moisture content but the moisture content of soil sample upon receipt in the lab.

3.3.2 Electrodes

As discussed earlier in Section 2.5.2, electrically conductive geosynthetic (EKG) material has been developed in past researches to overcome corrosion of electrodes during direct current application. The EKG material does not undergo corrosion during electrolysis. Hence the EKG material would be unaffected by the naturally acidic condition of peat. To further enhance the conductivity of EKG material, copper strips were included in the design of electrical vertical drain (EVD). The EVD is similar to prefabricated vertical drains (PVD) used to increase drainage during preloading ground improvement technique for soft soils. The EVD has added function of being electrically conductive while acting as a drain.

Commercially available prefabricated electrical vertical drain (EVD) comprising of a copper foil sandwiched between two layers of electrically conductive polyethylene ribbed pieces was used in this study. The EVD has a core made up of electrically conductive polyethylene with a nominal width of 100 ±3mm and a nominal thickness of 3mm encasing a 90mm wide copper foil. The entire core was then encased in a layer of non-woven filter geotextile.

3.4 Laboratory Test Setup

For a better understanding and closer representation of the field conditions, the experiment set-up for this study was designed with vertical electrodes and horizontal EO flow. A small scale rectangular test tank and a large scale cylindrical test tank were designed and fabricated for the EO consolidation of peat and organic soil. The small rectangular test tank was used for studies under planar conditions. The large cylindrical test tank was designed for tests with radial electrode configurations. The large cylindrical test tank is also used to investigate the effects of upscaling, using a 1D grid electrode configuration for EO consolidation.

3.4.1 Small scale experiment setup

The electro-osmosis experiments of laboratory scale were conducted in 250mm x 110mm x 250mm (width x breadth x height) rectangular glass tanks. The whole test set up was based on *anode closed – cathode opened* condition where water removed from the system was not replaced at the anode to reduce soil water content and induce consolidation. Figure 3.3 shows the small test tank setup. This setup was adopted after a series of preliminary tests were carried out on the electrodes (Kaniraj *et al*. 2011). Figure 3.4 shows the evolution of the electrode width and arrangement for the preliminary tests. Volume of the soil specimen in the small scale experiment was $0.0055m^3$.

Initially the full width of the EVD was used as electrodes in the test. To further investigate the 2-dimensional (2D) electro-osmotic flow, the full width EVD was reduced to smaller strips (Kaniraj *et al*. 2011). By using a representative of a parallel and staggered electrode arrangement, the 1 anode – 1 cathode and 2 anodes – 1 cathode layout was developed. Preliminary test results indicated that the staggered electrode arrangement, 2 anodes – 1 cathode, was more effective in terms of settlement, water content reduction and gain in strength. To simulate field condition of full-width EVD spaced at 1.5m, the EVD for test setups were reduced to 15mm. In the 2 anodes – 1 cathode arrangement, the centre-to-centre distance of the EVD strips were 55mm, equivalent to 0.35m in the field. The electrodes of the same polarity were spaced at a closer distance to minimize the ineffective area of the EO process.

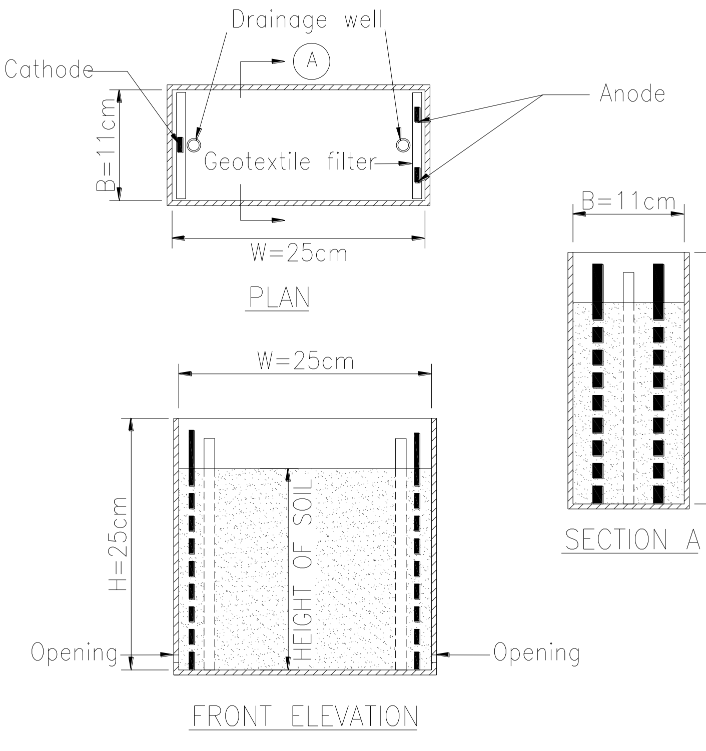


Figure 3.3: Laboratory small scale experimental tank layout

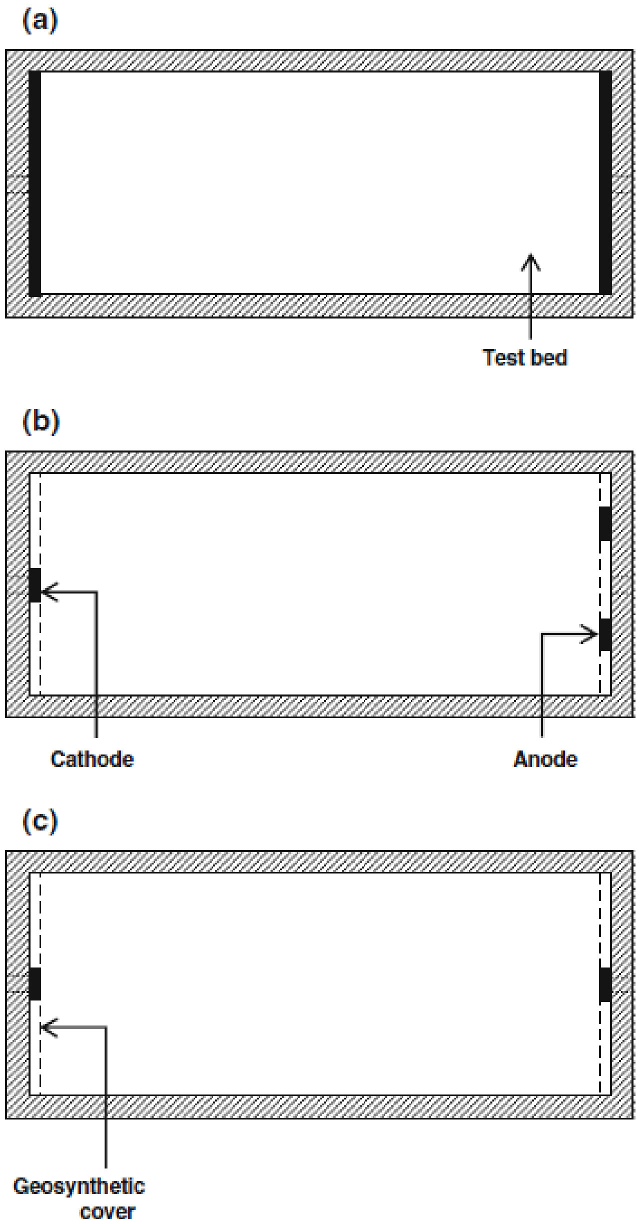


Figure 3.4: Plan view of electrode configurations. (a) Full width electrode (b) 2 anodes – 1 cathode (c) 1 anode – 1 cathode (Kaniraj *et al*., 2011)

As the experimental work progressed, a drainage arrangement to simulate field/actual working conditions was adopted, where drainage from bottom is not necessarily viable. A perforated 17mm diameter PVC pipe sheathed in filter geotextile was used as drainage wells where water collected was pumped at predetermined intervals. Determination of the pumping intervals is discussed in Chapter 6. The arrangement with drainage well can be seen as Figure 3.5. Figure 3.6 shows the plan view of the small scale test tank.

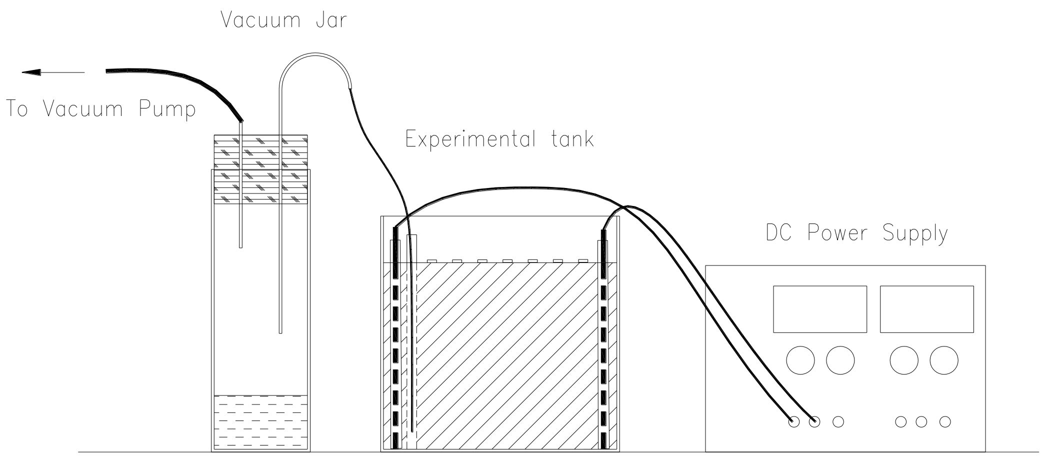


Figure 3.5: Small scale experiment set-up

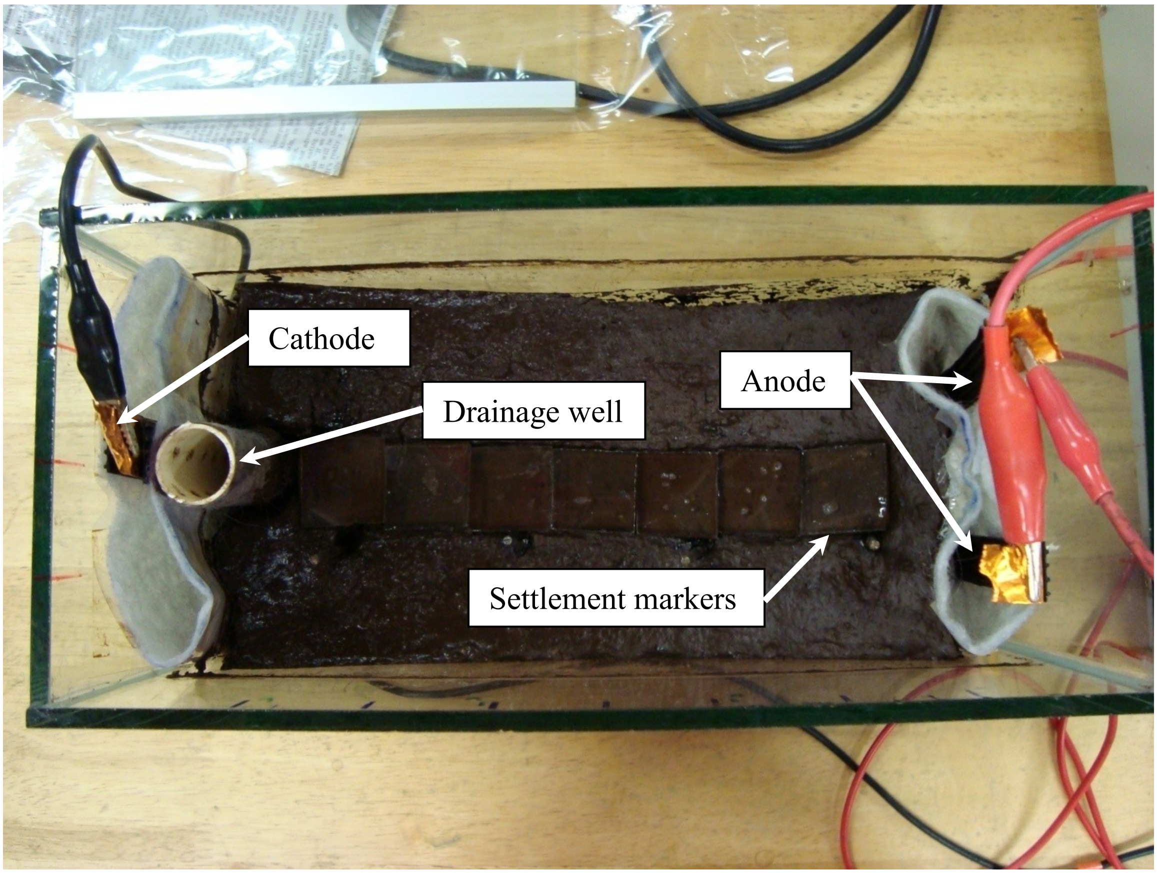


Figure 3.6: Plan view of small scale test tank

3.4.2 Large scale experiment setup

The large scale experiments is designed and planned for investigation of 2D flow in electro-osmotic consolidation on a larger scale. Main areas of study in the large scale experiment are the electrode configurations and applied voltage gradient. Two radial electrode configurations, one 1D electrode configuration and control test tank without electrode were studied.

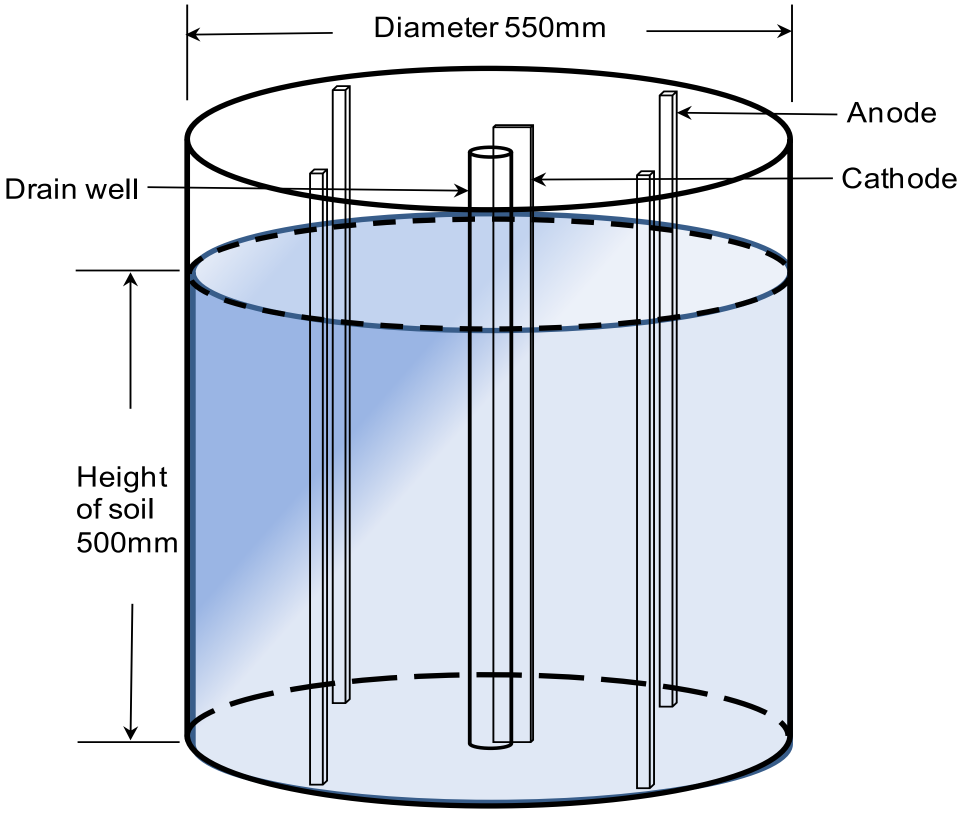


Figure 3.7: Large scale experiment set-up

Figure 3.7 shows the large scale experiment set-up. The electro-osmosis experiments were conducted in 550mm diameter by 550mm deep polyethylene (PE) tanks. Volume of test soil specimen for the EO consolidation is 0.119m^3. Direct current (DC) was supplied to the test apparatus using laboratory direct current power supply. The whole experimental system was also based on *anode closed – cathode opened* condition where water removed from the system was not replaced at the anode to enable reduction of soil water content. A drainage well was included to simulate field/actual working conditions was adopted. The drainage well consisted of a perforated 50mm diameter PVC pipe sheathed in filter geotextile. Water collected in the drainage well was extracted at predetermined intervals. Figure 3.8 shows the schematic layout plan of the tests with square (R4), hexagon (R6) and 1D grid electrode arrangements. Figure 3.9 shows the plan view of the tests with square (R4), hexagon (R6) and 1D grid electrode configurations.

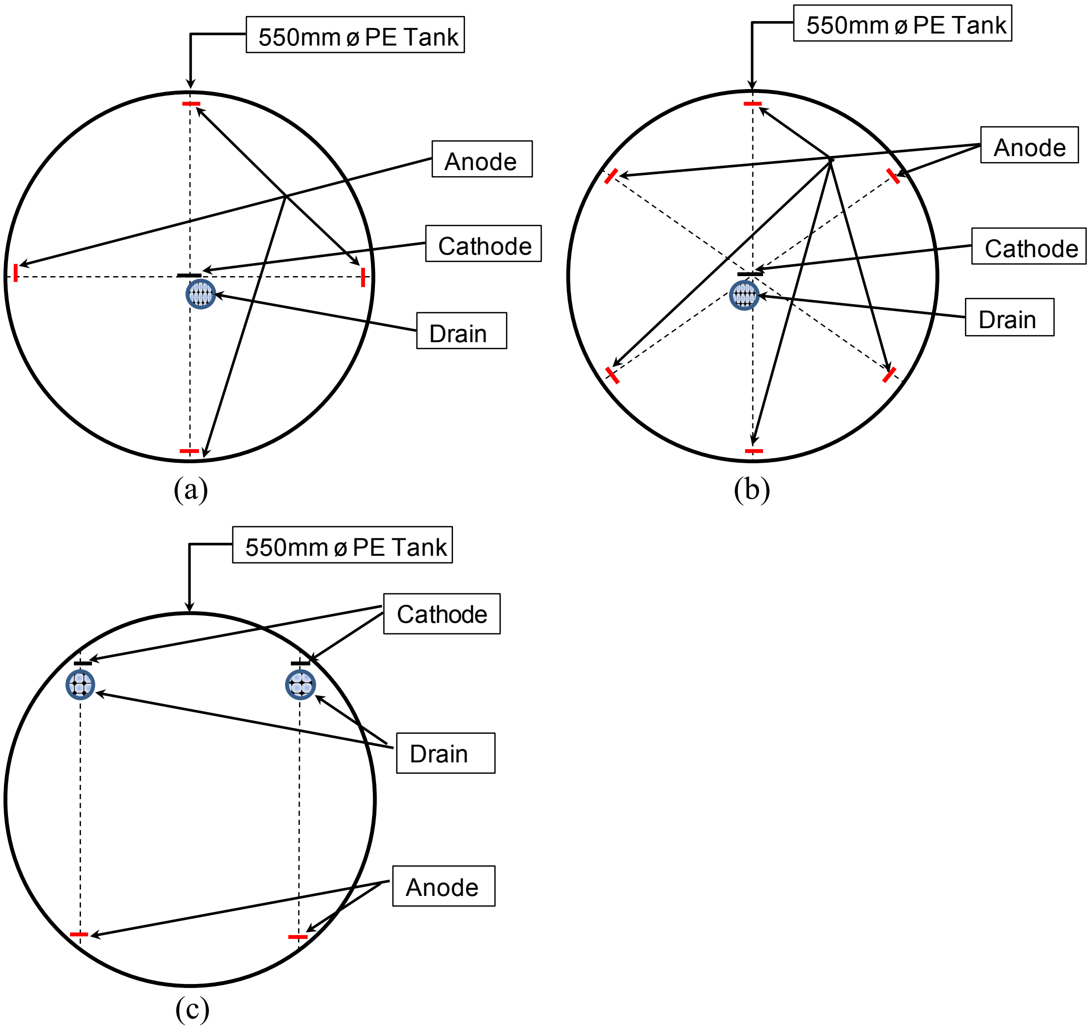
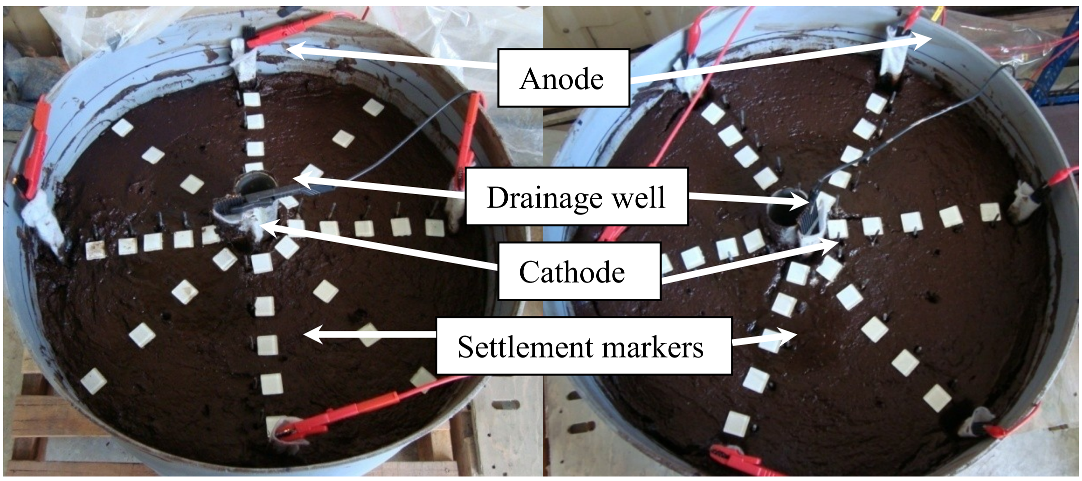
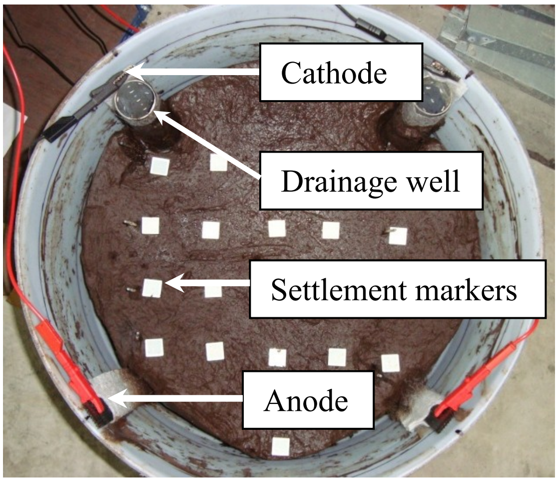


Figure 3.8: Schematic layout plan of test tank. (a) Square (R4), (b) Hexagon (R6) and (c) 1D grid electrode configurations



(a) (b)



(c)

Figure 3.9: Plan view of test tank. (a) Square (R4), (b) Hexagon (R6) and (c) 1D grid electrode configurations

3.5 Experiment Procedure

3.5.1 Experiment procedure for small scale test

In general, the experiments were conducted according to the following procedures with certain adjustments made to suit where required.

Preparation of test soil

When peat was used as test material, the only preparation required was removal of large wood pieces and long roots. As the collected peat had high natural water content, it was hand mixed and left overnight before use. To ensure uniformity, the peat was hand mixed again before being placed in the test tanks. However, with organic soil, it was necessary to add water in order to obtain a slurry. The organic soil was mixed with a planetary mixer. The organic soil slurry was then transferred into a closed container until the required amount of material was collected. When the necessary amount of slurry was achieved, the entire slurry in the container was hand mixed for uniformity. The soil slurry was left in the closed container overnight to allow the slurry to reach equilibrium.

Preparation of EVD

A 240mm long EVD piece was cut from a roll of prefabricated EVD. The EVD piece was then further cut into 15mm wide by 240mm long strips. To form the anode, two EVD strips were placed 55mm apart and then encased in a geosynthetic filter. Similarly for the cathode, a single strip of EVD was encased in a geosynthetic filter. For both the anode and cathode EVDs, to expose the copper strip, a small portion of the polyethylene layers were removed at the top. The prepared EVDs were immersed in water before placement to saturate the geosynthetic filter covers. This was done to prevent them from absorbing water from the soil specimen.

Preparation of drainage well

A drainage (collection) well was used to simulate actual field conditions where bottom drainage is not always possible. The drainage well was made from 17mm internal diameter and 220mm long PVC pipes wrapped with a layer of geotextile filter along the length and base. To allow water to drain into the drainage well, the length of the PVC pipe was perforated with tiny holes. When polarity reversal was not carried out, the drainage well was only placed near the cathode as seen in Figure 3.10(c).

Preparation of experimental tank

A glass tank with 110mm breadth x 250mm width x 250mm height was used for small scale laboratory experiments. Firstly the pre-soaked EVDs and drainage well were placed at the respective end of the test tank. The prepared peat or organic soil slurry was placed gradually in thin layers into the tank. Each layer was gently tamped with a wooden bar to remove any entrapped air. Layer by layer, the soil in the test tank was progressively filled until a thickness of about 200mm was achieved. 1cm square discrete glass plates or tiles were placed along the top of the soil test bed as settlement markers. The filled test tank was covered with a glass plate over a piece of polyethylene sheet to prevent loss of moisture due to evaporation. The prepared tank was left to stand overnight to attain equilibrium within the soil.

Control test (self weight consolidation)

For the control test, EVDs were not required for the self-weight consolidation test. The drainage well was also included in the test setup. The soil was filled in the same manner as the EO consolidation test tank to the same thickness of 200mm. The settlement markers were also placed. The prepared tank was also left to stand overnight, covered with a polyethylene sheet and glass plate cover.

Pre-experimental / Initial tests

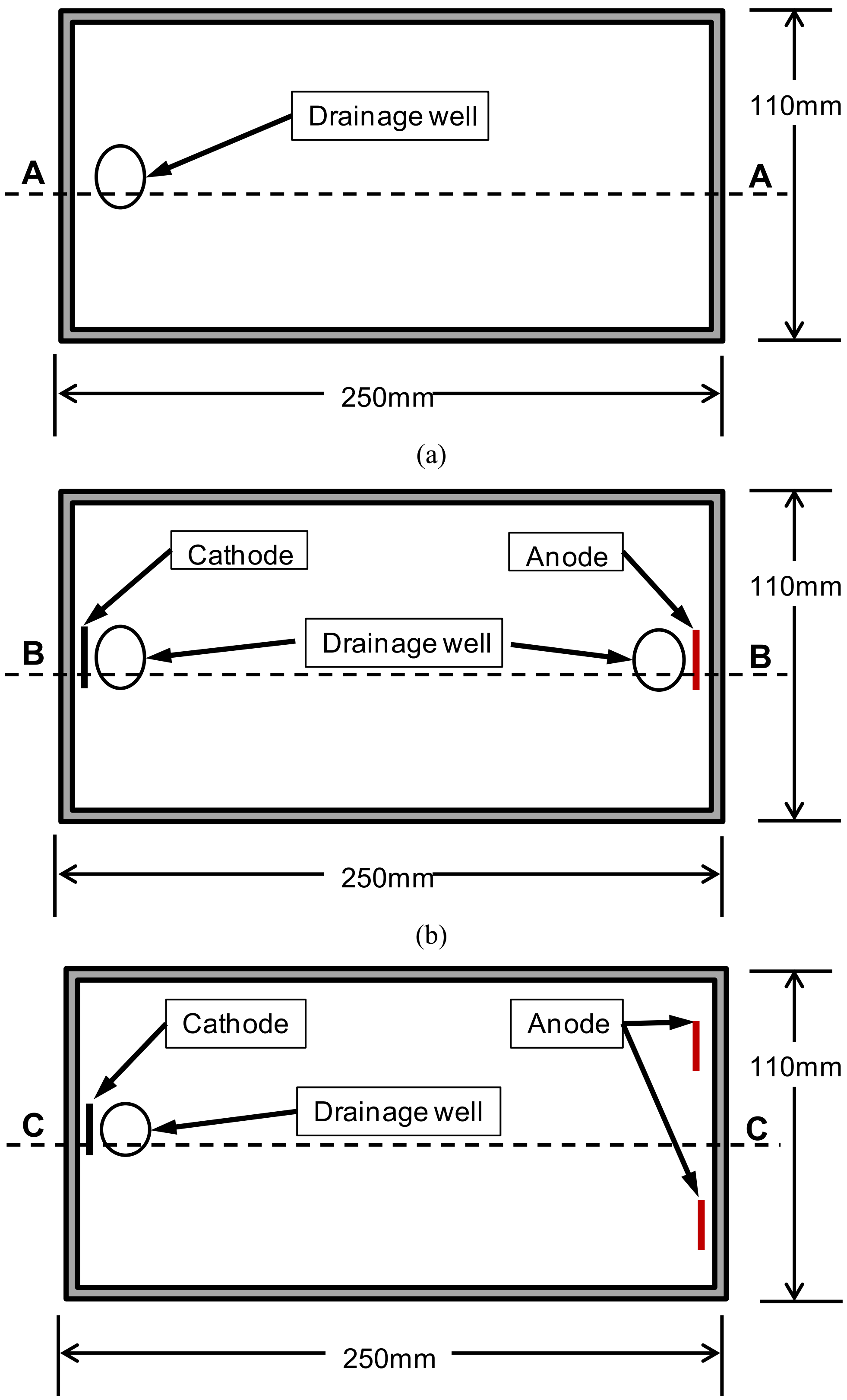
For each of the prepared test tanks, the initial moisture content was obtained as soon as the tanks were filled. Samples from two different locations were collected for moisture content tests. Laboratory vane shear tests were carried out on two selected locations at the top of the test bed. Before the start of DC application, the initial height of the soil bed was measured using digital vernier caliper.

Electro-osmotic (EO) consolidation test

The EVDs were connected to a direct current (DC) benchtop power supply. The power supply was adjusted to supply the required voltage between the anode and cathode EVDs. The collection of water was carried out at intervals during the day and is left to accumulate in the drainage well for 12 hours overnight. A vacuum jar, connected to a vacuum pump, was used to draw out water collected in the drainage well. Care was taken to ensure the vacuum applied was sufficient to draw water without creating additional suction to the test bed. Water collected from the anode and cathode were collected and measured separately. pH of the collected water was also determined whenever there was sufficient amount of water collected (>50ml). Settlement of the test bed was measured daily. Voltage and current measurement were obtained with a multimeter daily.

Post consolidation tests

After completion of the EO consolidation tests, laboratory vane shear tests were conducted at the top of the test bed at 70mm, 125mm and 180mm from the cathode. Following that, Shelby tubes were pressed into the test bed at the three locations. The Shelby tubes were removed with minimal disturbance to the specimen inside. Laboratory vane shear tests were also carried out on the specimens at the bottom of the Shelby tubes. The soil specimen was then extruded from the Shelby tube and divided into several segments. The moisture contents of the soil segments were determined to obtain the average moisture content along the height of the test bed. pH of the soil was measured according to ASTM D4972.



(c)

Figure 3.10: Plan view of small scale test for (a) control test; (b) 1cathode-1anode electrode configuration; (c) 1cathode-2anode electrode configuration

Figure 3.10(a) shows the plan view of the control test setup including section A-A. Figure 3.10(b) and (c) show the plan view of the EO test setups. Sections B-B and C-C span between the anode and cathode. Seven settlement markers were placed along each respective section. Settlement and voltage measurements were taken along the sections as well. Current measures were done at the anode.

3.5.2 Experiment procedure for large scale test

The experiments were conducted according to the following procedures.

Preparation of test soil

To prepare the peat for use, large wood pieces and long roots were removed. The peat was mixed into a slurry to ensure uniformity. The peat slurry was then transferred into a closed container. The soil slurry was left in the closed container for approximately 24 hours to allow the slurry to reach equilibrium. The peat was mixed once again before placing for uniformity.

Preparation of EVD

A 520mm long full-width EVD piece was cut from a roll of prefabricated EVD. The EVD piece was then further cut into 15mm wide by 520mm long strips. The width of the EVD used in the experiment was reduced to 15mm from actual width of 100mm in attempt to scale the experimental setup to closer suit actual field spacing of 1.8m between electrodes. To form the electrodes, each strip of EVD was encased in a geotextile filter.

Preparation of drainage pipe

A collection well was used to simulate actual field conditions where bottom drainage is not always possible. This collection well was made from 50mm internal diameter and 520mm long PVC pipes sheathed with a layer of geotextile filter along the length and base. To allow water to drain into the collection well, the surface of the PVC pipe was perforated with tiny holes.

Preparation of experimental tank

A 550mm diameter by 550mm deep PE tank was used for the experiment. Firstly the EVDs and drainage well were position in the test tank according to the specified electrode arrangement. The prepared peat slurry was gradually placed in layers into the tank. Each layer was gently tamped during placing to remove any entrapped air in the slurry. The peat in the test tank was progressively filled until a thickness of about 500mm was achieved. 1cm square tiles were placed on top of the peat as settlement markers to aid settlement reading. Upon completion of the test tank preparation, a piece of polyethylene sheet was used to cover the tank to prevent loss of moisture due to evaporation. The prepared tank was left to stand overnight to achieve equilibrium in the soil.

Pre-experimental / Initial tests

For each of the prepared test tanks, the initial moisture content was obtained as soon as the tanks were filled. Laboratory vane shear tests were carried out on two selected locations at the top of the test bed. Before the start of direct current application, the initial height of the soil bed was measured from the top of the test tank using digital vernier caliper.

Electro-osmotic consolidation test

The EVDs were connected to a laboratory direct current power supply. The power supply was adjusted to supply the required voltage between the anode and cathode EVDs. After application of continuous direct current for 12 hours, the settlement of the test bed was measured. Water extracted from the drainage wells were collected and measured separately. A vacuum jar connected to a vacuum pump was used to draw out the water collected. pH of the collected water was also determined. Water collected in the drainage well was pumped at 3hr during the day and is left to accumulate for 12 hours overnight. Voltage and current reading were obtained using a handheld multimeter at 12 hour intervals for the duration of the test.

Post consolidation tests

After completion of the EO consolidation tests, laboratory vane shear tests were performed at the top of the test bed at selected locations. Following that, handheld Geonor vane was used to determine the undrained shear strength in the middle and bottom of the soil bed. Moisture content samples were also collected from top, middle and bottom of the soil bed to profile the changes in moisture content within the soil bed.

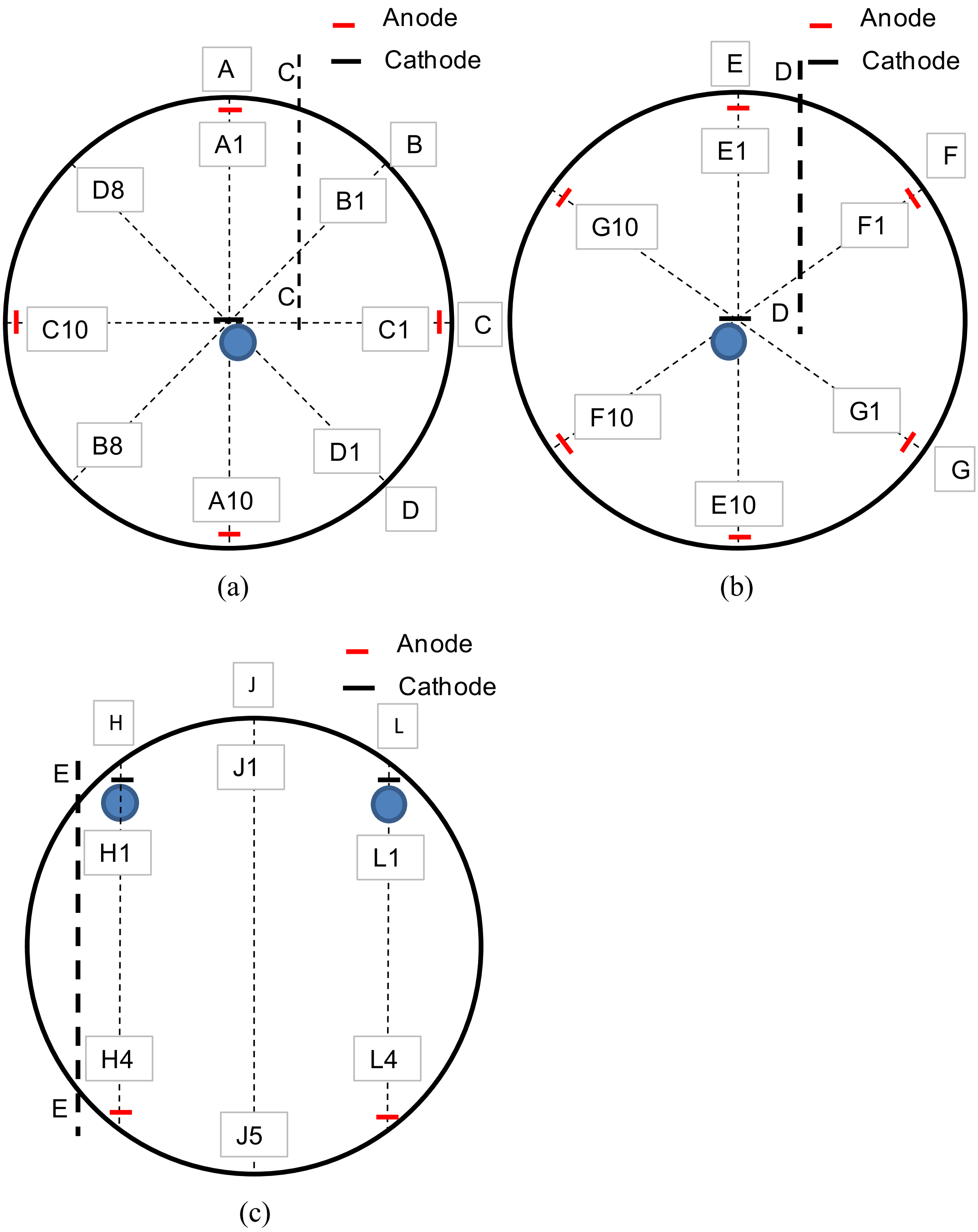


Figure 3.11: Plan view of large scale test tank with (a) 2-D square (R4); (b) 2-D hexagon (R6); (c) 1-D grid (G2) electrode configuration

Figure 3.11 shows the representative sections from each different electrode configuration used in the analysis and discussions in the following chapters. For the square electrode configuration, Figure 3.11(a), five settlement markers are placed between an anode and the cathode. For the hexagon electrode configuration, Figure 3.11(b), five settlement markers were also placed between an anode and the cathode. In the 1-D grid electrode arrangement, shown as Figure 3.11(c), only four settlement markers were placed between the anode and the cathode.

3.6 Measurement of Variables/Instrumentation

Monitoring of the soil sample during EO consolidation tests were carried out to record the changes that occur throughout the test duration. Moisture content and undrained shear tests were carried out before and after each set of EO consolidation test. The following section lists the measurement and tests carried out for each EO consolidation test. The limitations, if any, of each measurement are also included.

3.6.1 Settlement measurement

Settlement markers ($1cm^2$ glass squares or tiles) were placed on top of the soil surface. A digital vernier calliper is used for measuring daily settlement. Top of the test tank is used as the datum or reference during measurements. Measurements were done at 24hr intervals for the small scale tests and 12hr intervals for the large scale tests.

3.6.2 Water collected measurement

In order to collect the water from the drainage wells, a vacuum jar is used. The vacuum jar is connected to a vacuum pump. Limitation of this water collection method is the large vacuum pump. To create sufficient vacuum in the jar while preventing addition suction to the surrounding soil, the vacuum pump was immediately switched on then off. Further preventive measure taken was the withdrawal of the water collection tube from the bottom of the drainage well once all water in the drainage well is drawn out. The water collected is measured in a graduated cylinder to obtain the volume. Colour of the water collected is also recorded.

3.6.3 pH measurement

Handheld pH meter, Hanna Instrument HI9024, is used to obtain pH values. pH value of the water collected is measured only when at least 50ml of water is available for pH measurement. Volume of less than 50ml would not give an accurate representation of actual pH.

Measurement of soil pH is done using the handheld pH meter in accordance to ASTM D 4972-01, Standard Test for pH of Soil.

3.6.4 Voltage measurement

Voltage measurements were conducted after water was removed from the drainage well. A handheld multimeter is used for measurement of voltage in the soil during EO consolidation test. The multimeter is included in parallel to the electrode system. Conductive steel rods were inserted into the soil specimen to serve as both markers and extension of the voltage probe. In the small scale test tank, the steel rods were 50mm in length. In the large scale test tank, the steel rods were 270mm in length. Limitation of the voltage measurements is the lack of continuous recording over the test duration. Voltage measurements were collected by hand using the handheld multimeter at 12-hour intervals during the test duration. Voltage measurements were taken using the cathode as the reference. Readings were taken at intervals between 0.16 to 0.84 normalised distances from the cathode. Voltage reading from the anode was also recorded.

3.6.5 Current measurement

Using the same handheld multimeter for voltage measurement, the setting was changed for current measurement. To obtain current reading, the multimeter is placed in series with the electrode-soil-power supply system. The multimeter was included in the electrical system between the anode and the power supply. Limitation of the current measurement is that the reading was only recorded at 12-hour intervals. Continuous recording was not available due to the prolonged test duration of minimum 192 hours.

3.6.6 Soil sampling after EO consolidation test

Thin-walled sampling tubes known as Shelby tube samplers were used to extract soil samples at the end of the EO consolidation test. The Shelby tube samplers were slowed pushed into the soil in the test tank. Then the Shelby tube samplers were carefully removed in order to minimise disturbance to the soil sample collected. Laboratory vane shear test at the bottom of the soil specimen was conducted on the soil in the Shelby tube samplers. After laboratory vane shear test, the soil in the Shelby tube sampler was extruded for moisture content test.

3.6.7 Moisture content of soil

Moisture content of the soil specimen was obtained according to ASTM D 2974, Test Methods for Moisture, Ash and Organic Matter of Peat and Other Organic Soils. Initial moisture content of soil specimen is measured before the start of EO consolidation test. At the end of EO consolidation test, the moisture content of the soil sample collected in Shelby tubes was tested. The soil sample in the Shelby tube samplers were extruded and divided into sections of between 20 to 30mm for moisture content tests.

In the large scale test tank, moisture content samples were collected after vane shear tests were done. The Shelby tube samplers could not be used due to their limited length and the depth of the soil in the large tank. For the large scale test tank, the moisture content samples were collected from the middle and the bottom of the test soil specimen. The collection of samples was done after the soil was excavated to the predetermined middle and bottom of the test specimen.

3.6.8 Laboratory vane shear test

Laboratory vane shear test was done to obtain values of undrained shear strength of the soil specimen. A 12.5mm vane was used. The vane was inserted 12.5mm into the soil to be tested. Laboratory vane shear test was carried out before the start of the EO consolidation test to obtain values of initial shear strength. After completion of the EO consolidation test, laboratory vane shear was also conducted at the top of the soil. Shear strength at the bottom of the soil specimen was obtained by testing the soil samples collected in the Shelby tube samplers.

3.6.9 Geonor handheld vane shear test

In the large scale test tank, the laboratory vane shear tests were only conducted at the top of the soil. To obtain the shear strength at different depths of the large scale test tank, Geonor handheld vane was used. The shear strength was obtained from the middle and bottom of the soil in the test tank. A guide was inserted to the full depth of the soil in the test tank to gauge the total depth of the soil after EO consolidation. The total depth is used to determine the middle and bottom section of the soil specimen.

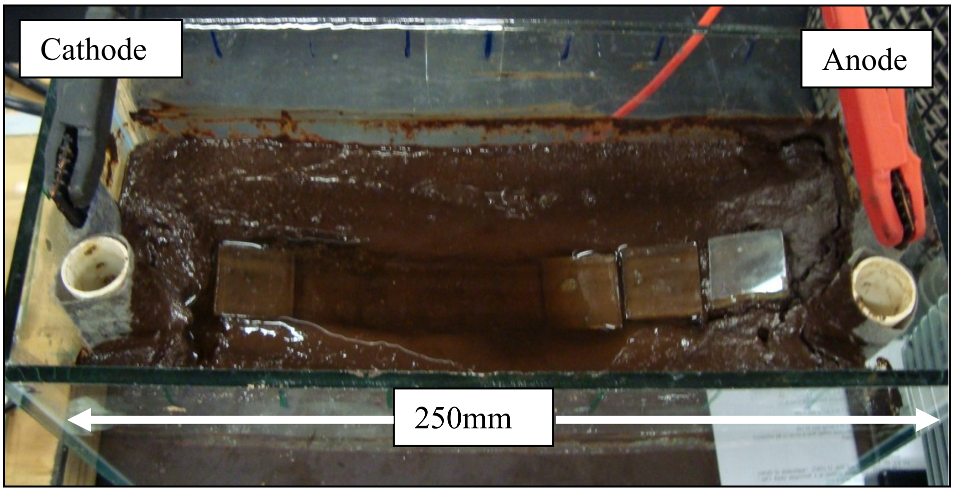
4 Effect of Voltage Gradient on EO Consolidation of Peat and Organic Soil

4.1 Introduction

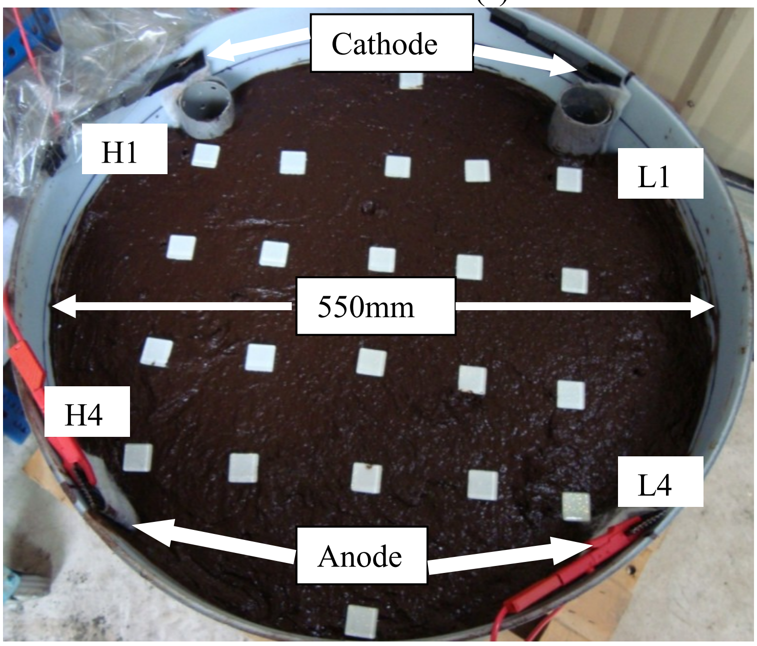
This chapter presents the observations and findings of the series of tests carried out to investigate the effect of voltage gradient during EO of peat and organic soil. This series of tests were carried out using fixed voltage gradient for both small and large test tanks. Further to that, incremental voltage gradient was also applied on peat and organic soil using the small scale test setup. A set of tests with application of constant current was included to assess the effects of fixed current on organic soil. The series of tests are listed in Table 3.1. Discussions on the observations and findings for the series of tests are also included in this chapter.

4.2 Effect of fixed voltage gradient of 80V/m, 100V/m and 120V/m during EO of peat

Tests on the effects of voltage gradient were carried out in the small and large scale test setups. Applied voltage gradients were 80V/m, 100V/m and 120V/m. The small scale tests were carried out with a single electrode configuration, where only one cathode and one anode were used for the experiment. In the large scale tests, grid electrode configuration was used. The large scale tests were done to study electro-osmosis of peat under up-scaled condition.



(a)



(b)

Figure 4.1: Plan layout of the (a) small scale and (b) large scale test setup

Figure 4.1(a) shows the plan layout of the small scale test setup (250mmx110mmx250mm). Initial conditions of the peat are listed in Table 3.1. Initial moisture content was 592%, 549% and 564% for test with 80V/m, 100V/m and 120V/m respectively. Initial shear strength was 1.71kPa, 0.93kPa and 1.99kPa for test with 80V/m, 100V/m and 120V/m respectively. Figure 4.1(b) shows the plan layout of the large scale test setup (550mmø x 550mm) with grid electrode configuration. Initial moisture content and undrained shear strength is tabulated in Table 3.1. Initial moisture content for the test with 80V/m, 100V/m and 120V/m was 394%, 243% and 337% respectively. Initial undrained shear strength was 1.58kPa, 2.38kPa and 3.05kPa for test with 80V/m, 100V/m and 120V/m respectively.

4.2.1 Settlement profile of peat during EO tests

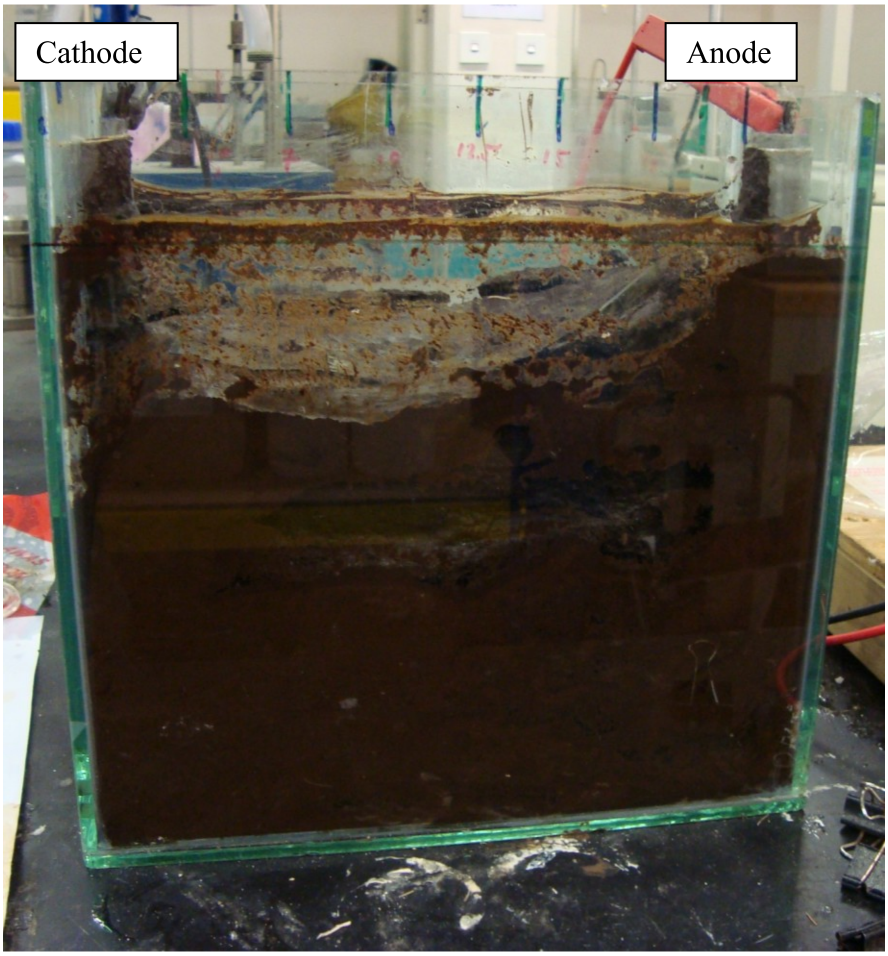


Figure 4.2: Front elevation of test with voltage gradient of 80V/m (1A/80/3/M) after completion of the EO test

Figure 4.2 shows the front elevation of the test with voltage gradient of 80V/m (1A/80/3/M) at the end of the eight day EO test. With the application of DC during EO treatment, settlement of the peat can be clearly observed. Variation of the applied voltage gradient resulted in varying settlement magnitudes, shown in the following section.

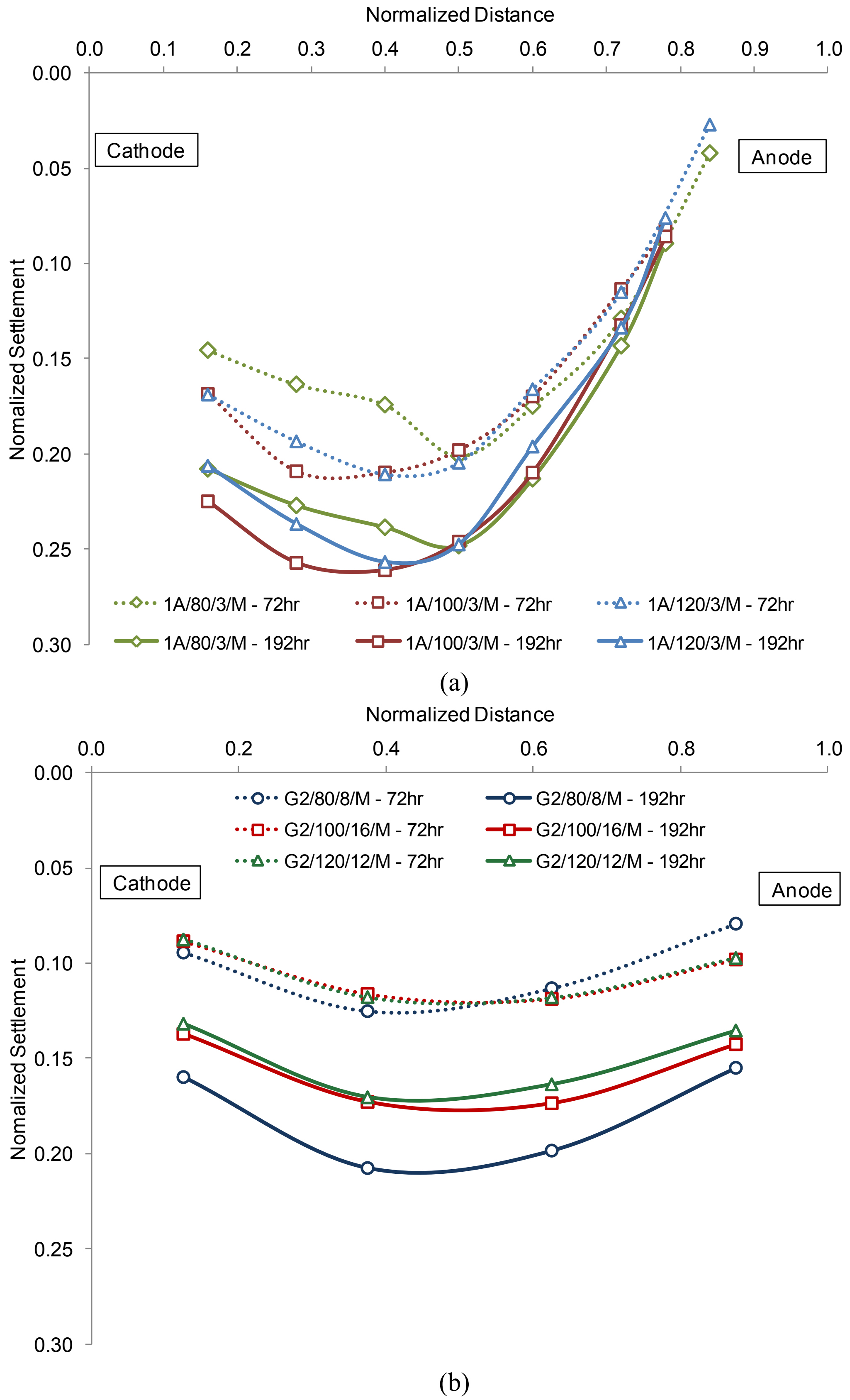


Figure 4.3: Normalized settlement profile of peat with time during (a) small and (b) large scale (along H1-H4) EO test with fixed 80V/m, 100V/m and 120V/m

Figure 4.3(a) shows the normalized settlement with time for the small scale tests with 80V/m, 100V/m and 120V/m. Recorded settlements were normalized using 200mm, the average initial height of the peat. In the tests with application of higher voltage gradient, cracks developed in the test sample. This showed that the peat also moved laterally during the tests. Hence for small scale tests, the measured settlement would not reflect the true amount of compression. The horizontal and lateral movement of the peat resulted in a void between the test sample and the test tank wall.

After 72hr of the application of direct current, all three tests show similar rate of settlement between normalized distances of 0.5 to 0.84. The test with voltage gradient of 80V/m underwent the lowest settlement with normalized settlement of 0.14 at 0.16 normalized distance from the cathode. Tests with voltage gradients of 100V/m and 120V/m show similar settlement profiles with less than 0.02 difference in the normalized settlement. At the end of the test at 192hr, normalized settlements between 0.5 to 0.72 normalized distances from the cathode continue to show little difference for all three tests. Between 0.16 to 0.5 normalized distances from the cathode, highest settlement is seen in the test with voltage gradient of 100V/m. The lowest settlement is seen in the test with voltage gradient of 80V/m. Maximum values of final normalized settlement at 192hr are 0.25, 0.26 and 0.26 for 80V/m, 100V/m and 120V/m respectively.

The relatively lower settlement of the test with voltage gradient of 120V/m is attributed to the crack in the peat near the anode, seen in Figure 4.4. The hairline crack that initially developed at the top of the peat near the anode gradually widened and deepened with time. The development of the crack resulted in gradual reduction of contact between the anode and the peat. Therefore, with the reduction of contact between anode and peat, the voltage transmitted to the peat is also reduced. Lefebvre and Burnotte (2002) discovered that manifestation of cracks in the soil had negative impact on the electro-osmotic consolidation process. The development of crack could also indicate that voltage gradient of 120V/m might be too high for the small scale test. Casagrande (1949) recommended against application of high voltage gradient as this would lead to cracks in the soil at the early stages of treatment which is detrimental to the electro-osmosis process.

(a)

(b)

Figure 4.4: Plan view of test with voltage gradient of 120V/m (1A/120/3/M) at (a) 72hr and (b) 192hr showing the development of the cracks in the peat

Figure 4.3(b) shows the normalized settlement in peat with time for the large scale tests. Recorded settlements were normalized using the average initial height of the peat, which was 500mm. Settlement profile shown is for the anode-cathode along H1-H4 of the test setup. Settlement profile of the second pair of anode-cathode along L1-L4 in the grid electrode configuration test is shown in the Appendix as A 7. The settlement profile of the large scale test shows lower variation between the anode and cathode, unlike the settlement profile of the small scale test.

At 72hr of the EO test, all three tests show similar rate of settlement. Values of the normalized settlement range from 0.08 to 0.12 for the three tests with minimal difference. By the end of the test, settlement of the three tests shows larger variation. Largest settlement is observed in the test with voltage gradient of 80V/m. Maximum normalized settlement is 0.21 at 0.38 normalized distance from cathode. Test with voltage gradient of 100V/m has maximum normalized settlement of 0.17. Settlement profile for test with voltage gradient of 120V/m did not show larger settlement than test with voltage gradient of 100V/m.

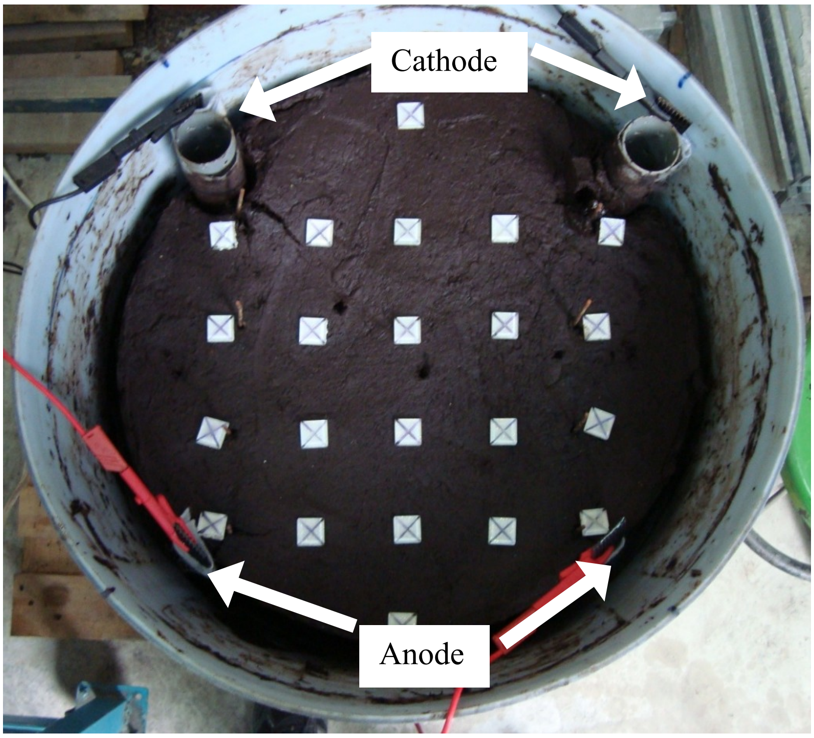


Figure 4.5: Plan view of grid (G2) electrode configuration test with applied voltage gradient 120V/m at the end of 384hr (16 days) test duration

Figure 4.5 shows the plan view of the grid (G2) electrode configuration test with applied voltage gradient 120V/m at the end of 384hr test duration. At higher voltage gradient of 120V/m and longer test duration of 384hr, only minor cracks formed in the vicinity of the electrodes. In the small scale test with voltage gradient 120V/m, large cracks formed through the peat during EO consolidation test. Cracks in peat during EO consolidation reduces electrode-peat contact, subsequently decreases the voltage transmitted through peat. It appears that with a larger peat volume, no major crack in the peat is observed with higher voltage gradient of 120V/m. Hence the application of 120V/m during field tests on EO of peat is not expected to result in formation of large cracks in the vicinity of the electrodes.

For the small scale EO test, application of 100V/m induced larger settlement in peat in comparison to the test with applied 80V/m. However, application of 120V/m did not result in larger settlement over the test with 100V/m. For the test with 120V/m, the lower settlement might be attributed to the crack near the anode. However, for the large scale tests, voltage gradients of 100V/m and 120V/m did not result in the expected larger settlement than voltage gradient of 80V/m. In the large scale tests, the highest normalized settlement is observed in the test with voltage gradient of 80V/m. The maximum normalized settlement in the 80V/m is 0.04 or 4% higher than the tests with 100V/m and 120V/m. For the second pair of anode-cathode in the grid electrode arrangement test, the normalized settlement of the 80V/m test also shows the highest magnitudes.

The dominant cause of settlement during EO treatment has not been identified at the moment. Volume reduction of peat could be due to consolidation and shrinkage. At the early stages of EO treatment, consolidation might be more dominant. While at the later stage of the test, as large volume of water is removed, shrinkage might contribute to volume reduction of peat.

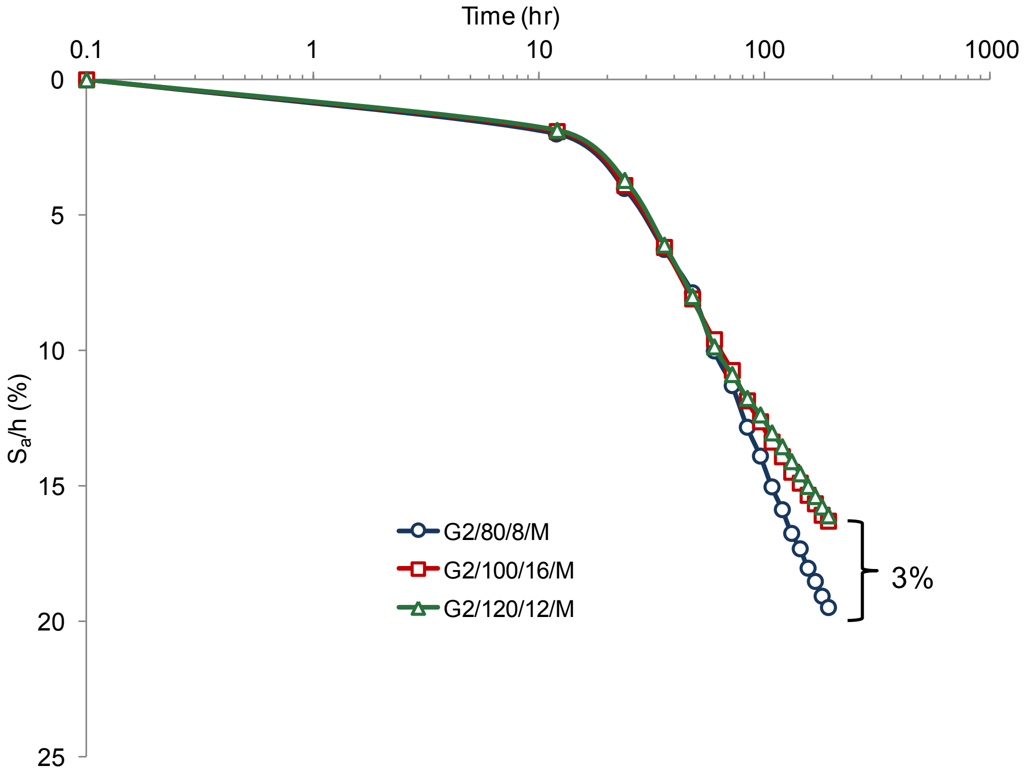
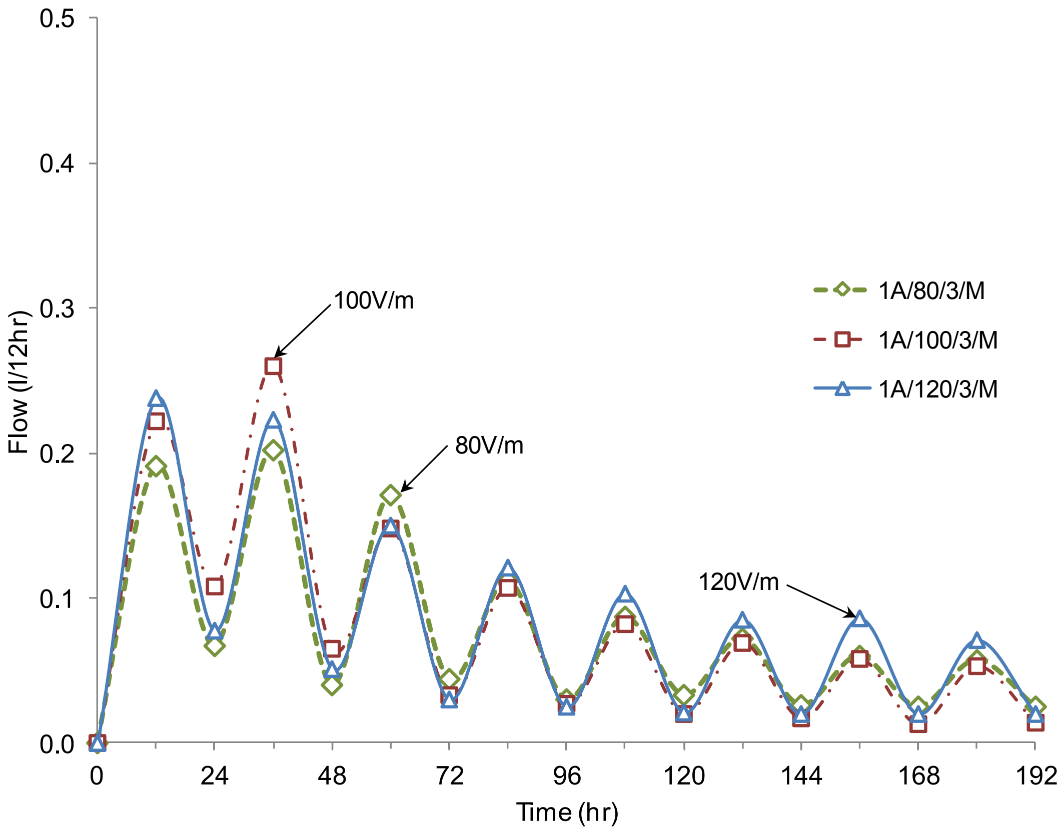


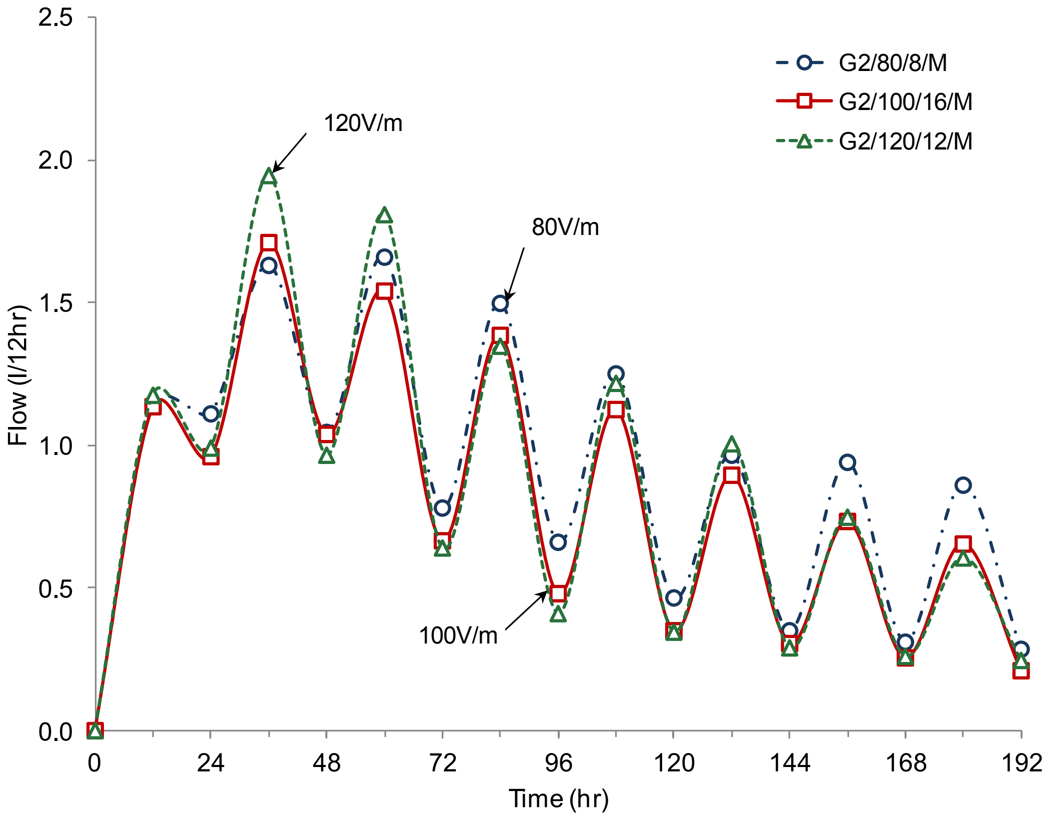
Figure 4.6: Normalized average settlement with time of peat during EO test in large scale test with grid electrode configuration

Figure 4.6 presents the normalized average settlement with time of peat during EO tests in the large scale test setup. As the large scale test consisted of two pairs of anode and cathode, the average settlement is used to observe the overall settlement of the test. Average settlement is obtained by averaging the data collected from all the 22 settlement markers placed on the peat (Figure 4.1b). The average settlement is then normalized using the average initial height of peat, 500mm. The overall normalized average settlement shows relatively similar settlement rate in all three tests at the early stage of the test. From 72hr onward, the settlement rates start to show noticeable differences with larger settlement observed in the 80V/m test. By 192hr, the overall normalized average settlement is 18%, 16% and 15% for voltage gradient of 80V/m, 100V/m and 120V/m respectively. The difference between the highest and lowest average settlement curve is 3%. The average settlement of the large scale test shows largest settlement in the test with voltage gradient of 80V/m.

4.2.2 Water collected during EO of peat



(a)



(b)

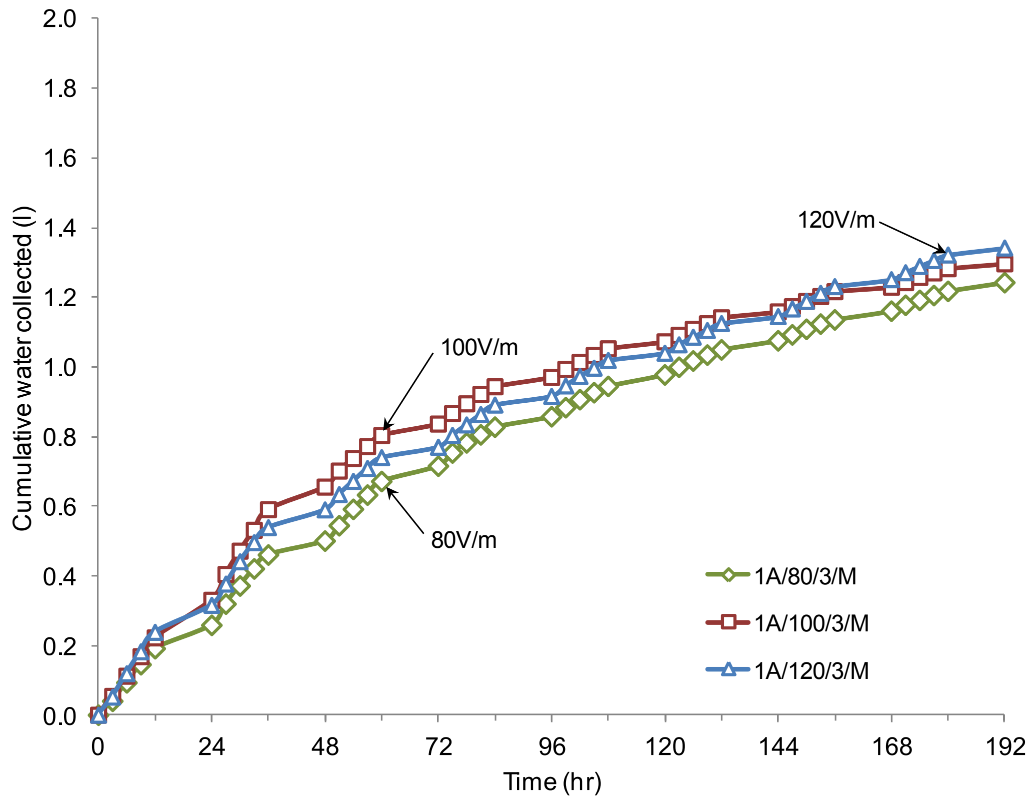
Figure 4.7: Average flow of water in (a) small and (b) large scale EO test with voltage gradient of 80V/m, 100V/m and 120V/m on peat

Figure 4.7(a) and (b) shows the flow of water collected at the cathode of the small and large scale EO tests. In the tests carried out, water in the drainage wells were collected at 3-hour intervals for 12 hours during the day. For 12 hours in the night, the water in the drainage well was not removed. Before the application of DC, water collected in the drainage well overnight after the preparation of the test tank was extracted and measured. This was recorded as the volume of water collected before the start of the EO consolidation test.

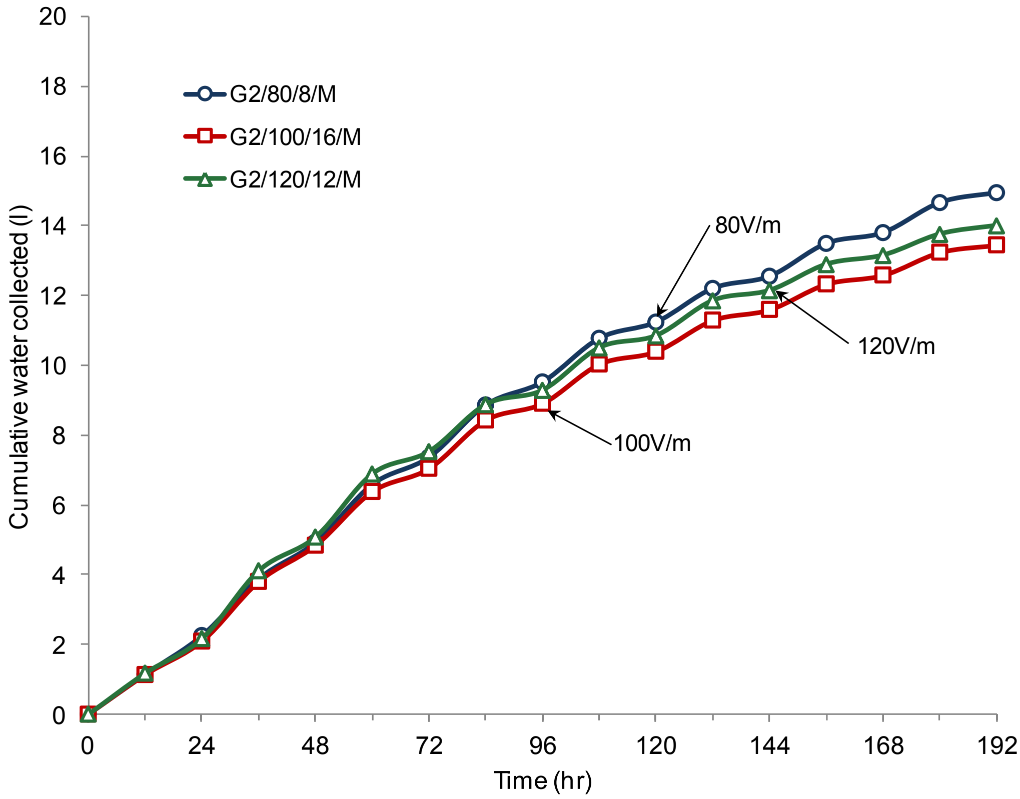
For the small scale EO tests (Figure 4.7a), higher flow is observed in the first two days of test followed by a gradual reduction of flow with time for all three tests. Highest flow is recorded in the test with voltage gradient of 100V/m with 260mℓ/12hr at 36hr. The highest flow in the 80V/m and 120V/m tests is 202mℓ/12hr and 238mℓ/12hr at 48hr and 24hr respectively. The trend of high flow in the initial two days of testing is also reported by Asadi *et al*. (2010), when electrokinetic testing was carried out under open anode – open cathode test setup. In the study, Asadi *et al*. (2010) noted the increase in flow after two days of testing, which incidentally were the peak values of flow recorded during the test. Following the initial high flow values, the flow went on to show a gradually declining trend with time, where a minimum rate was observed after 10 days. Eykholt and Daniel (1994) also observed the comparatively higher initial flow in their test on kaolinite.

Figure 4.7(b) shows the average flow in the large scale EO tests of the drainage well near H1 (Figure 4.1b). Flow pattern for the other pair of anode-cathode in the grid electrode configuration test is shown as Appendix A 8. For the large scale test, the average flow shows a different trend from the small scale tests. Both drainage wells in the grid electrode configuration tests did not show higher average flow at 12hr of the test. However, highest average flow is still observed on the second day of testing. The occurrence of the peak average flow shows similarity to the small scale tests. Another similar trend to the small scale test observed in the large scale test is the gradual reduction with time of flow.

For the drainage well near H1, highest average flow is 1.94ℓ/hr in the test with voltage gradient of 120V/m. The peak flow for voltage gradient of 80V/m and 100V/m is 1.63ℓ/12hr and 1.71ℓ/12hr respectively. The peak flow for test with voltage gradient of 80V/m occurred at 60hr which is later than the other two tests. It can also be observed that the reduction of average flow in the test with voltage gradient of 80V/m is lowest among the three tests.



(a)

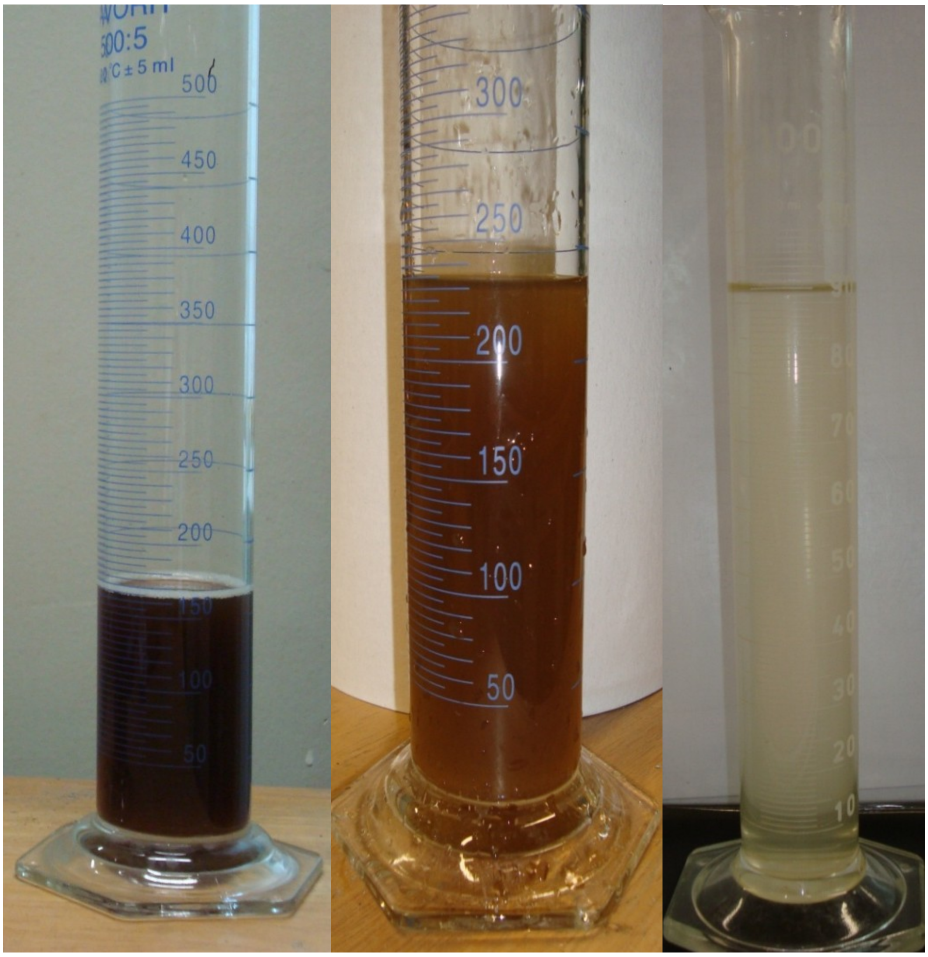


(b)

Figure 4.8: Cumulative water collected at cathode during (a) small and (b) large scale EO test with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.8(a) shows the cumulative water collected at the cathode in the small scale test. The volume of water collected at the cathode before start of DC application was 0.026ℓ, 0.033ℓ and 0.031ℓ for voltage gradient of 80V/m, 100V/m and 120V/m respectively. Highest volume of water collected is in the test with voltage gradient of 120V/m. The total volume of water collected is 1.242ℓ, 1.296ℓ and 1.341ℓ for voltage gradient of 80V/m, 100V/m and 120V/m respectively. In the three tests, between 48 to 60hr, the cumulative volume of water collected is already half the total volume of water collected. The test with voltage gradient of 80V/m consistently shows the lowest volume of water collected. Between 24 to 144hr, test with voltage gradient of 100V/m shows highest volume of water collected. However, from 144hr onwards, a reduction in the flow of the 100V/m is observed. In this period of time, higher volume of water is collected in the test with voltage gradient of 120V/m. The reduction of water collected from the test with voltage gradient of 100V/m might be due to trapped water in the void between the peat and glass tank wall. The trapped water was difficult to extract and could not be accounted for in the total volume of water collected. Hence the lower volume of water collected in the test with voltage gradient of 100V/m between 144 to 192hr compared that that of the test with voltage gradient of 120V/m.

Figure 4.8(b) shows the cumulative water collected at the drainage well near H1 during the large scale EO test. In the first 48 hours of the test, cumulative water collected show similar volumes for all three tests. As the test progressed, tests with voltage gradient of 80V/m and 120V/m show higher cumulative volume of water collected. From 60hr onward, test with voltage gradient of 100V/m shows the lowest cumulative volume of water collected. At 96hr, test with voltage gradient of 80V/m shows the highest cumulative volume of water collected. This trend of higher cumulative water collected with voltage gradient of 80V/m continued until 192hr. The total volume of water collected is 15.0ℓ, 13.5ℓ and 14.0ℓ for voltage gradient of 80V/m, 100V/m and 120V/m respectively.



(a) (b) (c)

Figure 4.9: Water collected at the cathode on (a) Day 1; (b) Day 3; (c) Day 8 during large scale EO consolidation test on peat

Figure 4.9(a) shows the water collected at the cathode at 24hr after the start of the large scale EO consolidation test. For the first few days of the test, the water collected was a very dark brown colour. With time, the colour of water collected gradually lightened to dark brown followed by brown (Figure 4.9b). After three to four days of the test, the water generally became light brown. This was followed by almost clear water collected after 8 days of the test (Figure 4.9c). It could only be postulated that the colour of the water collected is due to organic material. The change in colour from very dark brown to clear might indicate a reduction in organic material in the water collected. Unfortunately, no analysis of the water collected was carried out to ascertain its composition.

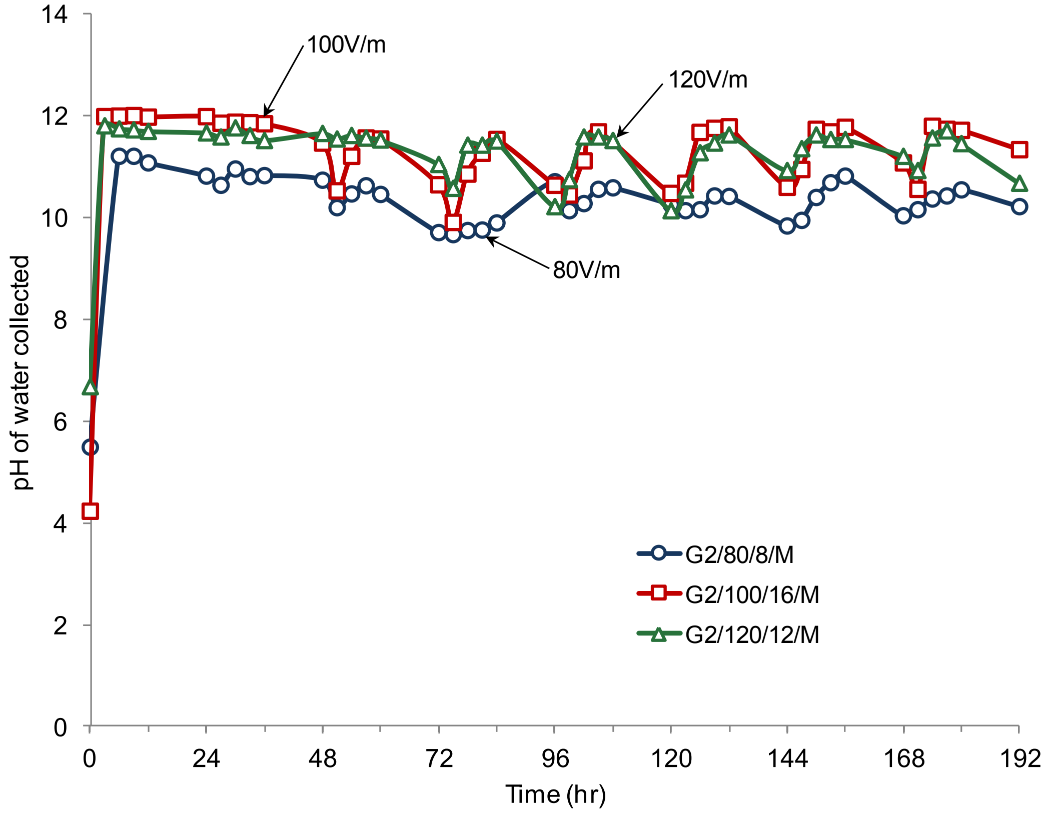


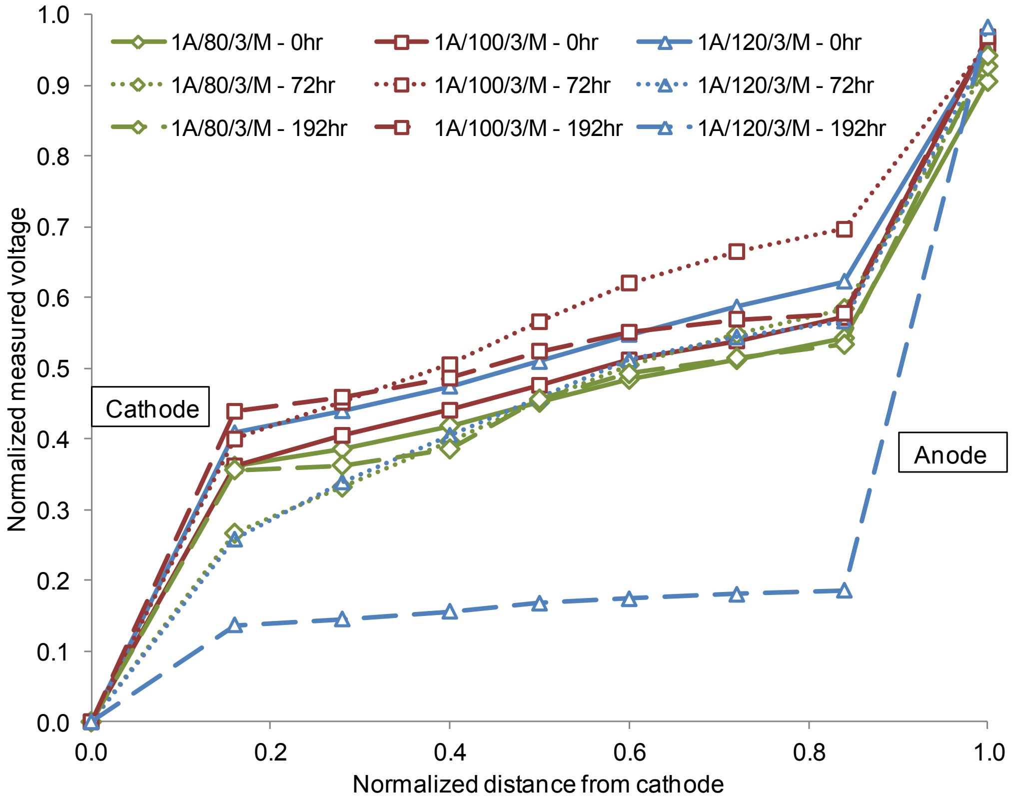
Figure 4.10: Variation in pH of water collected with time during large scale EO test with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.10 shows the variation in pH of the water collected at the cathode during large scale EO consolidation. The water collected in the drainage well overnight after preparation of the test tanks was extracted before the start of the test and pH was recorded. pH of the initial water collected was 5.49, 4.23 and 6.68 for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively.

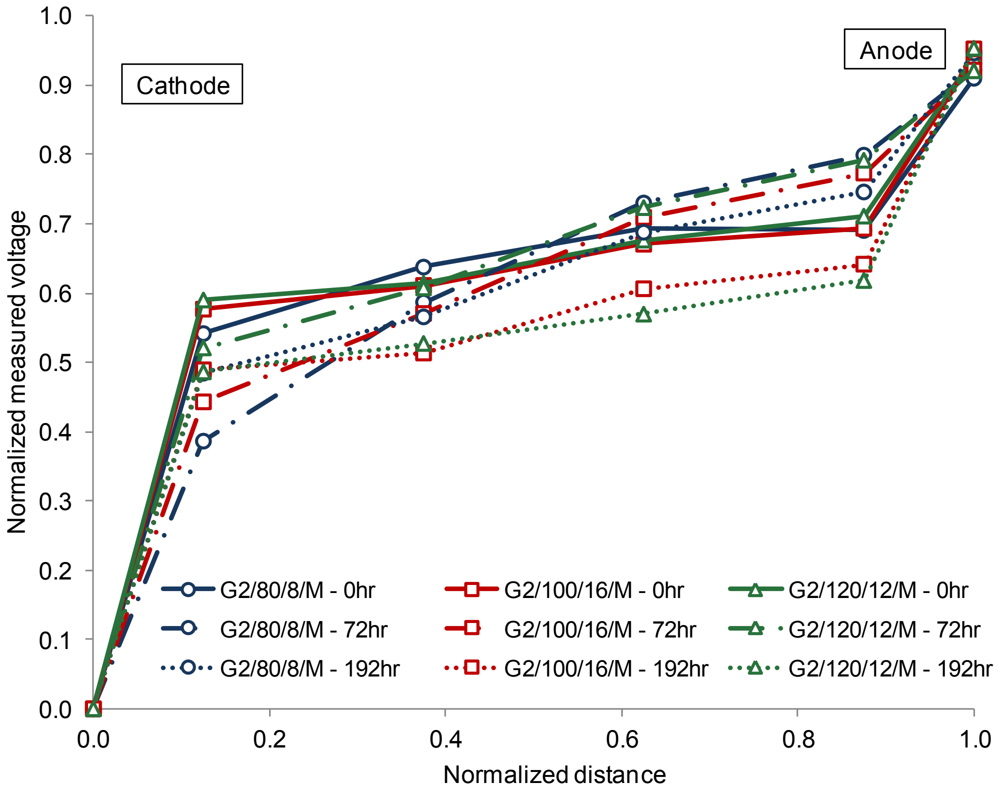
After application of DC, the pH of the water collected shows significant increase. At 3hr after the start of the test, pH of the water collected is 11.21, 11.99 and 11.81 for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively. This is in agreement with the electrokinetic test on peat where the pH of the cathode electrolyte showed increase during the test (Moayedi *et al*., 2014). The increase in pH of water collected at the cathode is an indication of the electrolysis process occurring at the electrodes during application of DC. Generation of hydroxide ions (OH^-) at the cathode increases the pH in the vicinity of the cathode. Higher pH also indirectly implies that higher amount of H_2 is generated at the cathode.

The pH of the water collected in the test with voltage gradient of 80V/m shows the lowest pH values among the three tests. The range of pH of water collected is from 9.67 to 11.21. Higher pH range is observed in the test with voltage gradient of 100V/m. The pH of water collected ranges from 9.91 to 12.01. Test with voltage gradient of 120V/m also shows a higher range of pH, ranging from 10.14 to 11.81. The lower range of pH in the test with voltage gradient of 80V/m is attributed to slower electrolysis process. Higher pH values are observed in the test with voltage gradient of 100V/m, indicating faster electrolysis processes. However, test with voltage gradient of 120V/m did not result in the highest range of pH in the water collected. No significant difference is observed in the pH of the tests with voltage gradient of 100V/m and 120V/m.

4.2.3 Voltage and current in peat during EO tests



(a)



(b)

Figure 4.11: Variation of normalized measured voltage transmitted through peat with time during (a) small and (b) large scale EO tests

Figure 4.11(a) and (b) shows the variation of normalized voltage transmitted through peat with time for small and large scale EO tests with voltage gradient of 80V/m, 100V/m and 120V/m. For the large scale test, the measured voltage shown is along H1-H4. Measured voltage of the second pair of anode-cathode in the large scale test is shown in Appendix A 1. The measured voltage was normalized using the applied voltage of each respective test.

From Figure 4.11(a), all three small scale EO tests show voltage losses near the electrodes. This is seen as the drop in measured voltage between the cathode and the first voltage probe (at a normalized distance of 0.16). The other voltage drop is observed between the last voltage probe (at normalized distance of 0.84) and the anode. The loss of voltage at the cathode and anode reported by Bjerrum *et al.* (1967) and Lo *et al*. (1991) during EO consolidation in clay is also observed in peat.

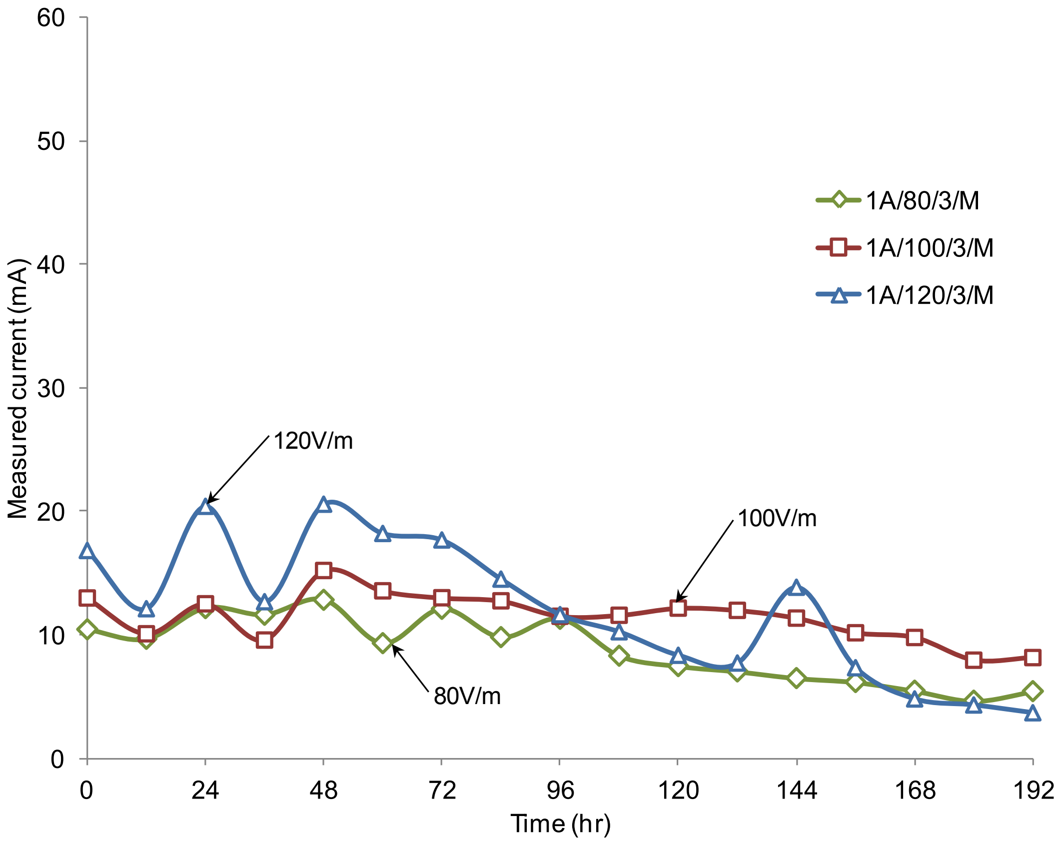
Initial voltage loss near the cathode ranges from 36 to 40% while near the anode, initial voltage loss ranges from 38 to 46%. With these losses, the initial applied voltage transmitted through peat between the first and last voltage probe is 18%, 21% and 22% for tests with voltage gradient of 80V/m, 100V/m and 120V/m respectively. As the test progressed, voltage losses at the electrodes show increase with time. At the end of the test, voltage losses of the test with voltage gradient of 80V/m did not show significant increase with the voltage transmitted of 18%. For the test with voltage gradient of 100V/m, there is an increase in voltage losses at the electrodes and the final voltage transmitted reduces to 14%. Highest increment in voltage loss near the anode is observed in the test with voltage gradient of 120V/m. At 192hr (Day 8), the voltage loss near the anode increases exponentially to 81%. Near the cathode, voltage loss is 14%, resulting in only 5% voltage transmitted through the peat.

Test with voltage gradient of 120V/m exhibited a loss of more than 80% at the anode region at the end of the test. This reduction in voltage is attributed to the crack in the peat near the anode, seen in Figure 4.4. As the crack developed, the contact between the anode and peat gradually reduced. With this reduction, the voltage transmitted to the peat is also reduced, hence the increased voltage loss in the vicinity of the anode.

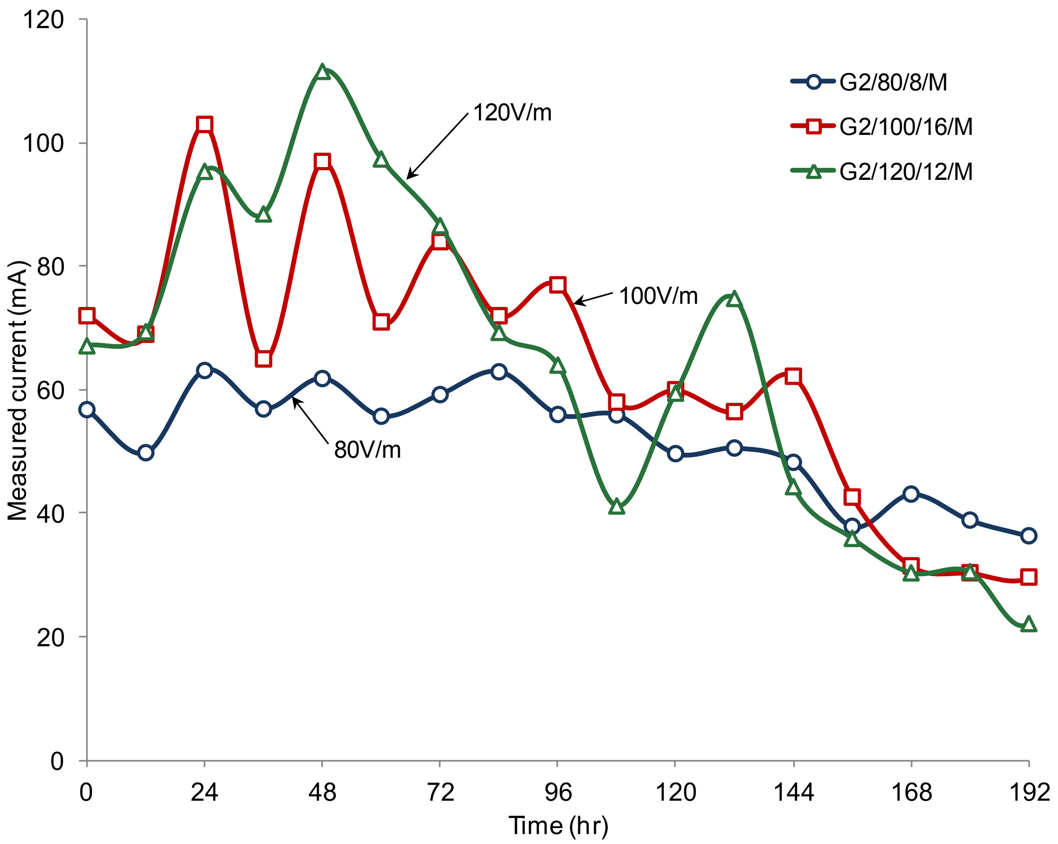
Figure 4.11(b) presents the variation of voltage in the peat with time during large scale EO test. The general trend of voltage distribution in peat of the large test is similar to the trend in small scale test. Voltage probes near the cathode and anode also show voltage loss between electrodes and peat. In the large scale test however, the losses near the cathode is as high as 59%, which is approximately 10% higher than the small scale test. A probable cause in the higher losses is the placement of the drainage well adjacent to the cathode. The drainage well reduces the cathode and peat contact area. The reduction in contact area in turn may reduce the voltage transmitted to the peat.

At the start of the test, recorded voltage loss near the cathode ranges from 54 to 59%. Voltage loss near the anode ranges from 29 to 31%. Initial voltage transmitted to the peat between the first and last voltage probe is 15%, 11% and 12% for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively. After three days of testing, voltage losses near the cathode and anode show reduction. The voltage transmitted to the peat is 42%, 33% and 12% for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively. At 192hr, voltage loss near the anode is higher in tests with voltage gradient of 100/m and 120V/m compared to that of test with voltage gradient of 80V/m. Voltage transmitted to the peat is 26%, 15% and 14%. A similar trend in the normalized measured voltage in peat is observed for the second pair of anode-cathode in the large scale test, seen as Appendix A 1.

The reduction in voltage transmitted through peat is attributed to the drying of peat in the vicinity of the anode as water flows away from the anode during EO. From Figure 4.8(b) presented earlier, tests with voltage gradient of 100V/m and 120V/m have higher average flow. This results in higher movement of water from the anode toward the cathode and higher reduction in moisture content in the vicinity of the anode. The lower moisture content of the peat reduces conductivity and decreases the voltage transmitted (Asadi and Huat, 2009, and Asadi *et al.*, 2009).



(a)



(b)

Figure 4.12: Variation of measured current with time in peat during (a) small and (b) large scale EO test with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.12(a) shows the variation of measured current through the peat for the small scale EO test. From the graph, it can be observed that higher voltage gradient induced higher current in peat. However, at the first 36 hours of the test, the measured current for 80V/m and 100V/m showed little difference. Larger variation in measure current occurred in the first 48 hours. Highest measured current is in the test with voltage gradient of 120V/m with a maximum of 20.6mA. As the test progressed, the measured currents exhibit a decreasing trend with highest reduction observed in the test with voltage gradient of 120V/m. The higher reduction in measured current of the test with voltage gradient of 120V/m is attributed to the development of a crack near the anode of the test peat. The crack caused discontinuity in the peat, hence reducing the contact between the anode and peat.

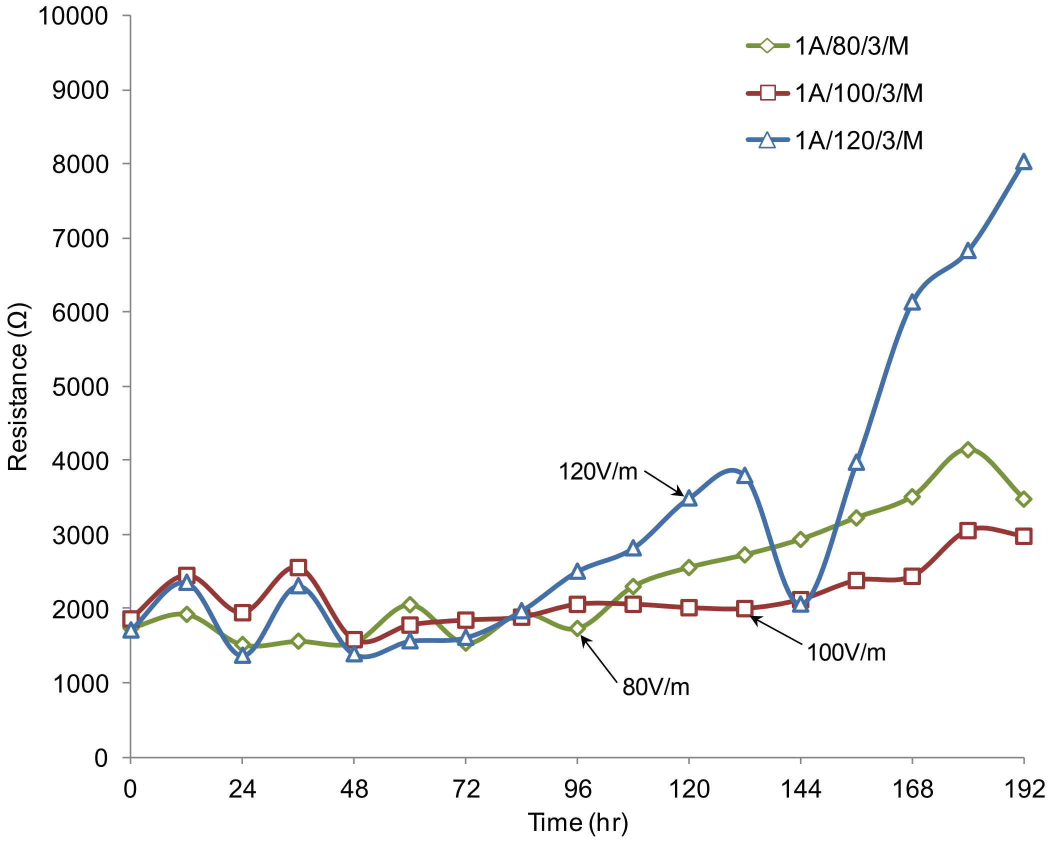
In the test with voltage gradient of 120V/m, a sudden increase in measured current is observed at 144hr. This sudden increase is attributed to a possible short circuit of the electrical system. In a laboratory study by Ng *et al*. (2007), a crack had formed near the anode and sudden increase in current was observed twice during the electro-osmotic treatment. Ng *et al*. (2007) attributed the sudden spike in current to water flowing into the crack and shorting the electrical system.

Figure 4.12(b) shows the variations in measured current through peat with time for large scale EO tests. Higher applied voltage gradient induced higher current in the peat, a trend that is observed in the small scale EO tests. Another similarity to the small scale test is the gradual reduction of measured current with time.

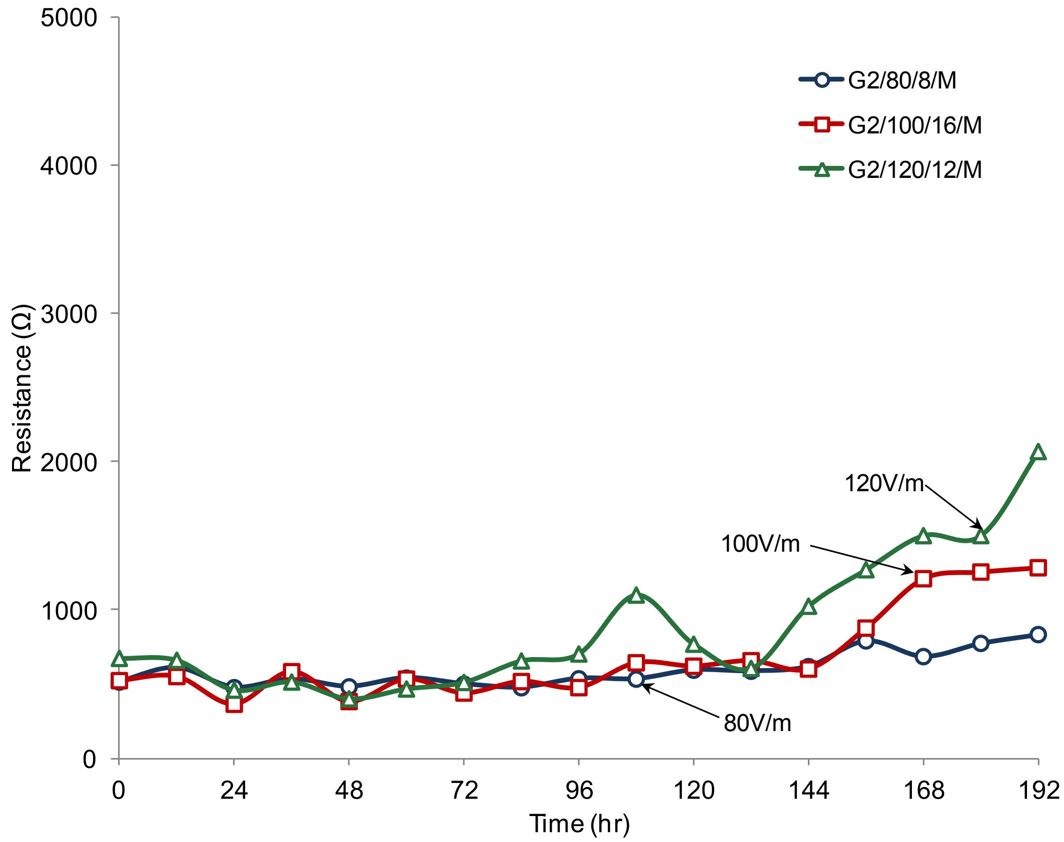
Lowest measured current is observed in the test with voltage gradient of 80V/m while highest measure current is in the test with voltage gradient of 120V/m. The highest measured current in the voltage gradient of 120V/m is 112mA. Test with voltage gradient of 80V/m shows a lower rate of reduction in current through peat. In the test with voltage gradient of 120V/m, there is a sudden drop at 96hr and a sudden increase at 120hr. Unlike the small scale test, no significant crack occurred in the large scale test. The possible cause of the sudden drop and increase is not known. Appendix A 2 shows the measured current for the second pair of anode-cathode in the large scale grid electrode configuration test, where a similar trend in measured current is observed.

In both the small and large scale EO tests, measured current in the peat is higher in the first 72 hours (first three days) without significant signs of reduction in spite of fluctuations. This is reflected in the higher rate of settlement and EO flow for the same period. Casagrande (1949) attributed the decrease with time of current to drying out of soil in the anode region where replacement of water was not available. Casagrande (1949) further elaborated that the drying process increased the resistivity of soil and reduced electric flow. The overall reduction of current with time could also be attributed to the contact losses at the electrode-soil interface. During electro-osmosis, electrolysis of water generates gases at the electrodes. With the generation of gas, voids in peat might form due to gas bubbles. An increase in voids near the electrodes could lead to reduced contact between the electrodes and peat (Mitchell and Soga, 2005). In addition to that, drying of the area near the anode as well as the whole peat specimen reduces conductivity, which in turn increases resistivity of the specimen (Asadi and Huat, 2009, and Asadi *et al.*, 2009). The reduction of voids in the peat also increases soil resistivity (Huat *et al.*, 2014).

4.2.4 Resistance during EO of peat



(a)



(b)

Figure 4.13: Overall resistance of (a) small and (b) large scale EO tests with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.13(a) presents the variation in overall resistance with time during small scale EO tests. Resistance is calculated as the measured voltage divided by the measured current. Initial overall resistance upon application of DC is 1737Ω, 1860Ω and 1712Ω for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively. In the first 48 hours of the test, the overall resistance in tests with voltage gradient of 100V/m and 120V/m show higher fluctuation than that of 80V/m. From 84hr onward, all three tests show increase in overall resistance, with highest increase in the test with voltage gradient of 120V/m. Peak overall resistance for each test occur between 180hr to 192hr. The peak overall resistance is 4144Ω, 3053Ω and 8035Ω for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively.

In the test with voltage gradient of 120V/m, the sudden drop in overall resistance to 2062Ω at 144hr is attributed to possible short circuit of the electrical system as discussed earlier. This drop in resistance is reflected in the sudden increase in measured current through the peat at 144hr (Figure 4.12a). The generally lower overall resistance at the later stage of the test with voltage gradient of 100V/m might be attributed to trapped water between the peat sample and the test tank wall. The trapped water might result in increased conductivity, hence reducing resistivity.

Figure 4.13(b) shows the variation in overall resistance with time along H1-H4 of the large scale EO test. The initial overall resistance is 513Ω, 522Ω and 673Ω for tests with voltage gradient of 80v/m, 100V/m and 120V/m. The comparatively lower overall resistance of the large scale test might be due to the wider 30mm electrode used for the large scale test as compared to the 15mm wide electrodes used in the small scale test. This effect is observed in the higher measured current of the large scale tests, where it might be due to larger contact area of the electrode. The increasing trend in overall resistance for all three tests is observed from 96hr onwards. Towards the end of the test, highest overall resistance is seen in the test with voltage gradient of 120V/m. The maximum overall resistance is 833Ω, 1285Ω and 2069Ω for tests with voltage gradient of 80V/m, 100V/m and 120V/m.

For the small and large scale EO tests, increase of overall resistance is observed at the later stage of the test. This might be due to water removed from peat resulting in the drying of peat and reduction in conductivity. This is also observed as the reduction in measured current through peat for the same period of time. Highest reduction in measured current is observed in the test with 120V/m and this is reflected in the highest increase in overall resistance of the same test. On the other hand, the measured current through peat of the 80V/m test shows lower reduction and this is reflected in the lowest increase of overall resistance. The higher overall resistance of the tests with voltage gradient of 100V/m and 120V/m might be due to higher electrolysis process compared to that of the test with voltage gradient of 80V/m. With higher electrolysis process, the volume of gas generated is also higher. This might result in more void formation in the vicinity of the electrodes, further reducing electrode-soil contact and increasing resistance.

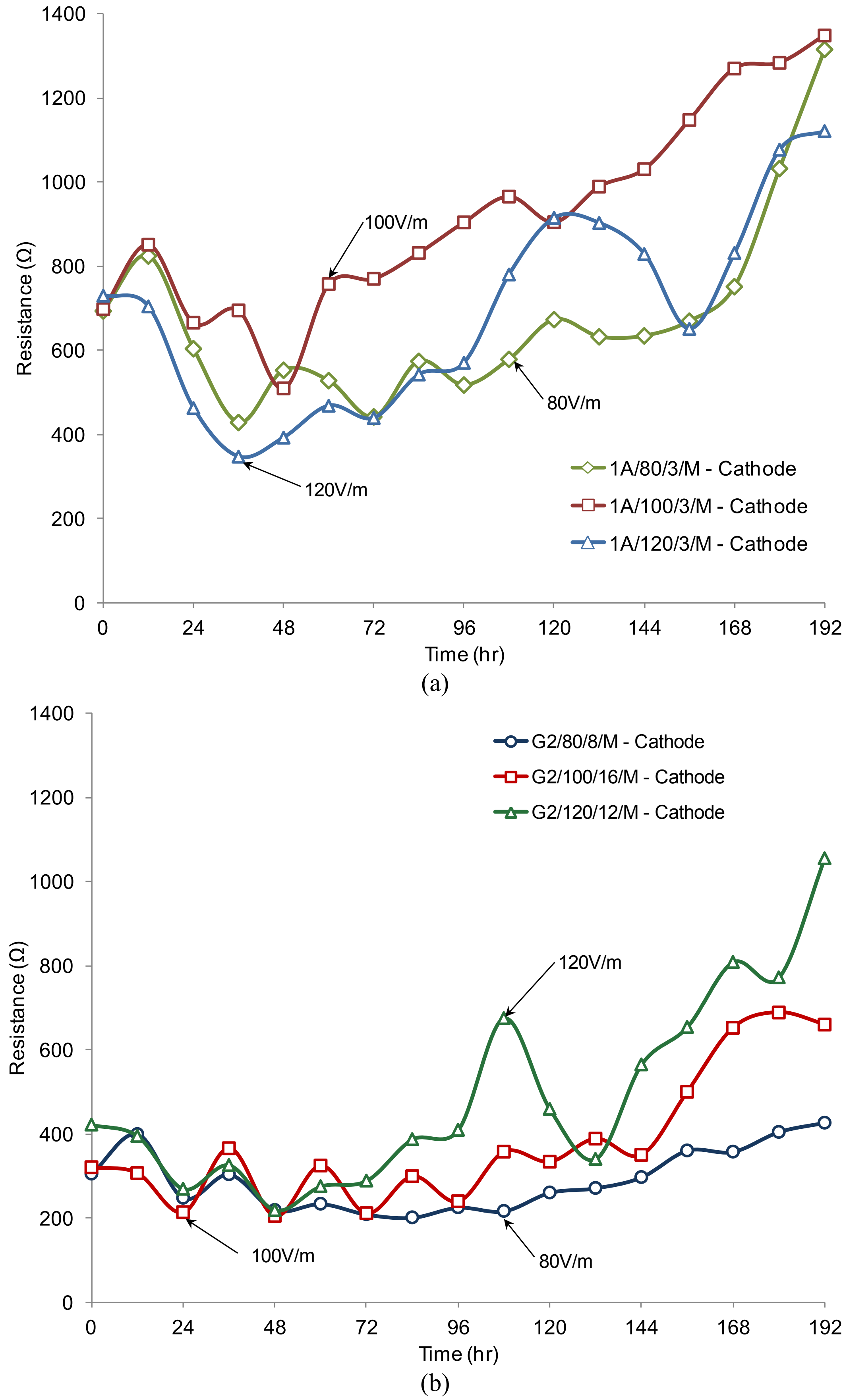
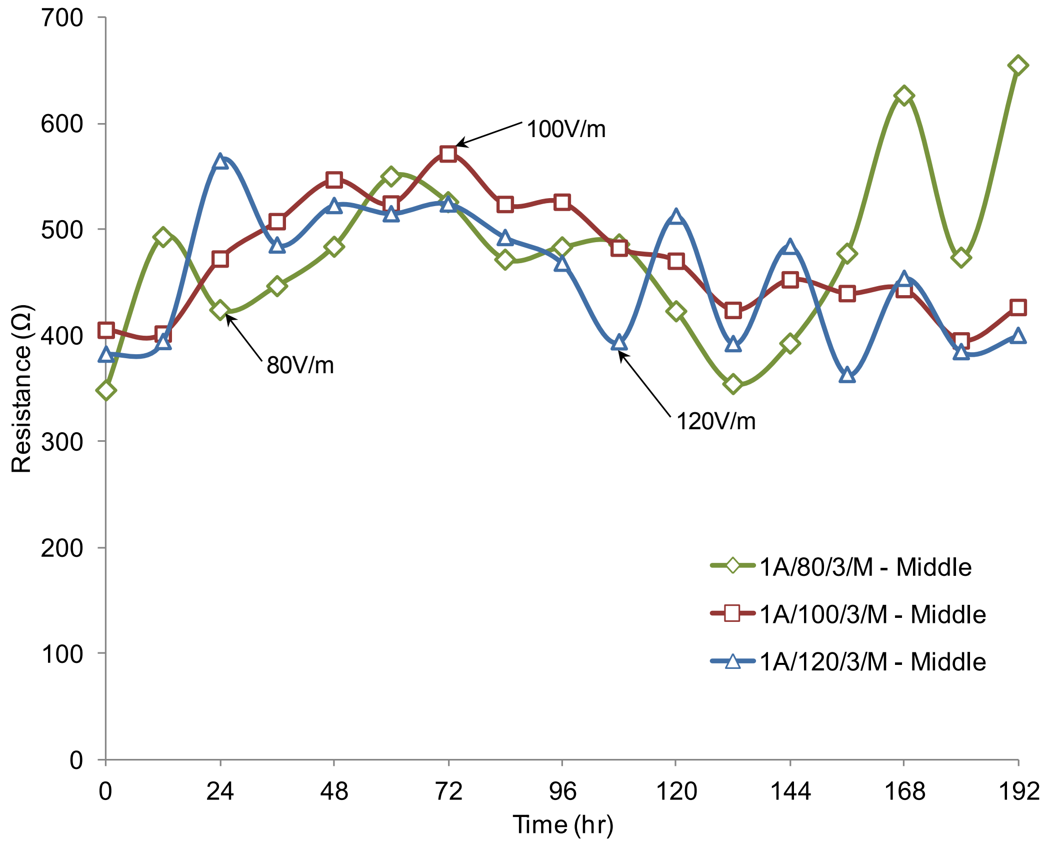


Figure 4.14: Resistance at the cathode region in the (a) small and (b) large scale EO tests with voltage gradient of 80V/m, 100V/m and 120V/m

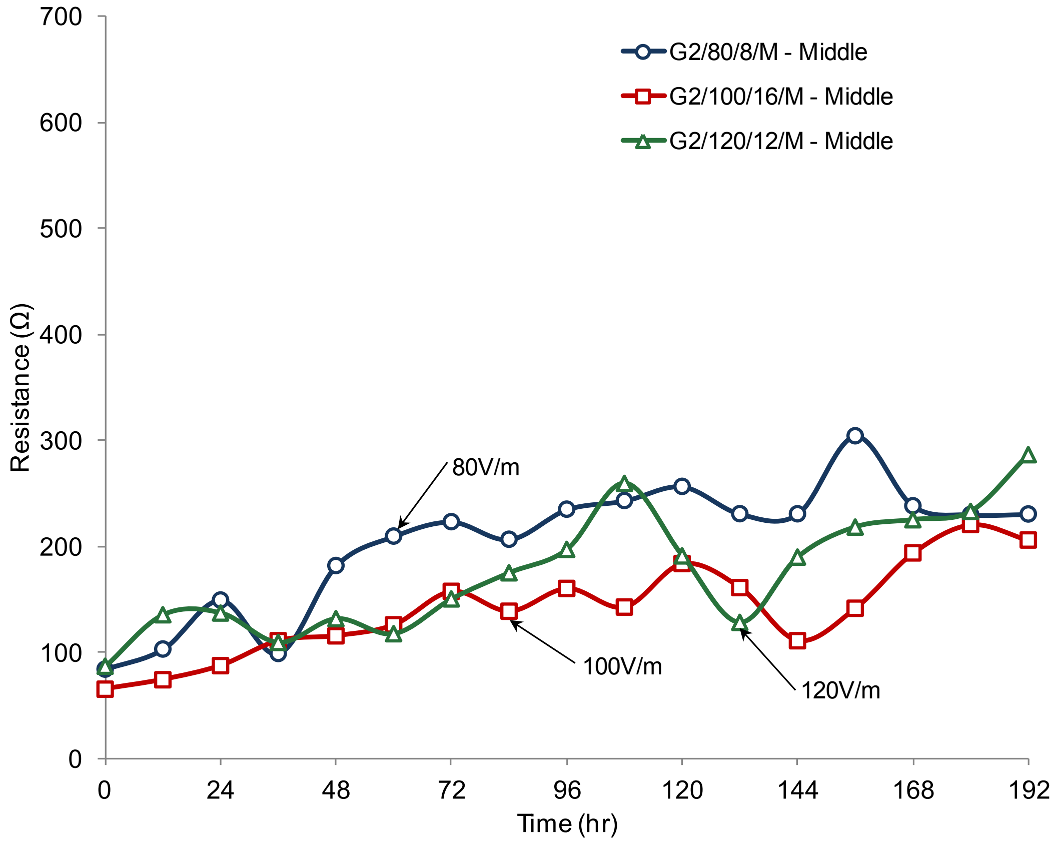
Figure 4.14(a) shows the variation in resistance at the cathode region of the small scale EO test. The cathode region is the area between the cathode and the first voltage probe at 0.16 normalized distance from the cathode. Initial resistance at the cathode region is 693Ω, 698Ω and 729Ω for test with 80V/m, 100V/m and 120V/m respectively. All three tests show reduction in resistance before 48hr followed by an increasing trend after that. Near the cathode, test with voltage gradient of 100V/m shows the highest resistance. Maximum resistance at the cathode region is 1315Ω, 1349Ω and 1121Ω for test with 80V/m, 100V/m and 120V/m respectively.

Figure 4.14(b) shows the resistance at the cathode region of the large scale EO test along H1-H4. Initial resistance of the cathode region is 305Ω, 320Ω and 422Ω for test with 80V/m, 100V/m and 120V/m respectively. Similar to the small scale test, the resistance of the cathode region also exhibit a slight reduction at the initial stages of the test. Increase in resistance is also observed at the later stages of the test. In the large scale test, the lowest cathode region resistance is in the test with voltage gradient of 80V/m while the highest is in test with voltage gradient of 120V/m. Maximum cathode region resistance occurred between 180hr and 192hr. Maximum resistance is 426Ω, 660Ω and 1055Ω for test with 80V/m, 100V/m and 120V/m respectively.

At the start of the EO tests, both the small scale and large scale tests exhibited a slight reduction in resistance near the cathode. This could be due to higher EO flow for the same time period, where larger volume of water is moved toward the cathode. The movement of water to the cathode increases conductivity and reduces resistance. With time and continued removal of water, resistance near the cathode starts to show gradual increase. This could be due to reduction in moisture content of peat in the vicinity of cathode at the later stage of the test. Increase in resistance could also be attributed to the hydrogen gas generation near the cathode. Gas bubbles causes voids to occur, resulting in increase of resistance (Mitchell and Soga, 2005). Hence, the resistance near the cathode could be due to a combination of water removal and gas generation.



(a)



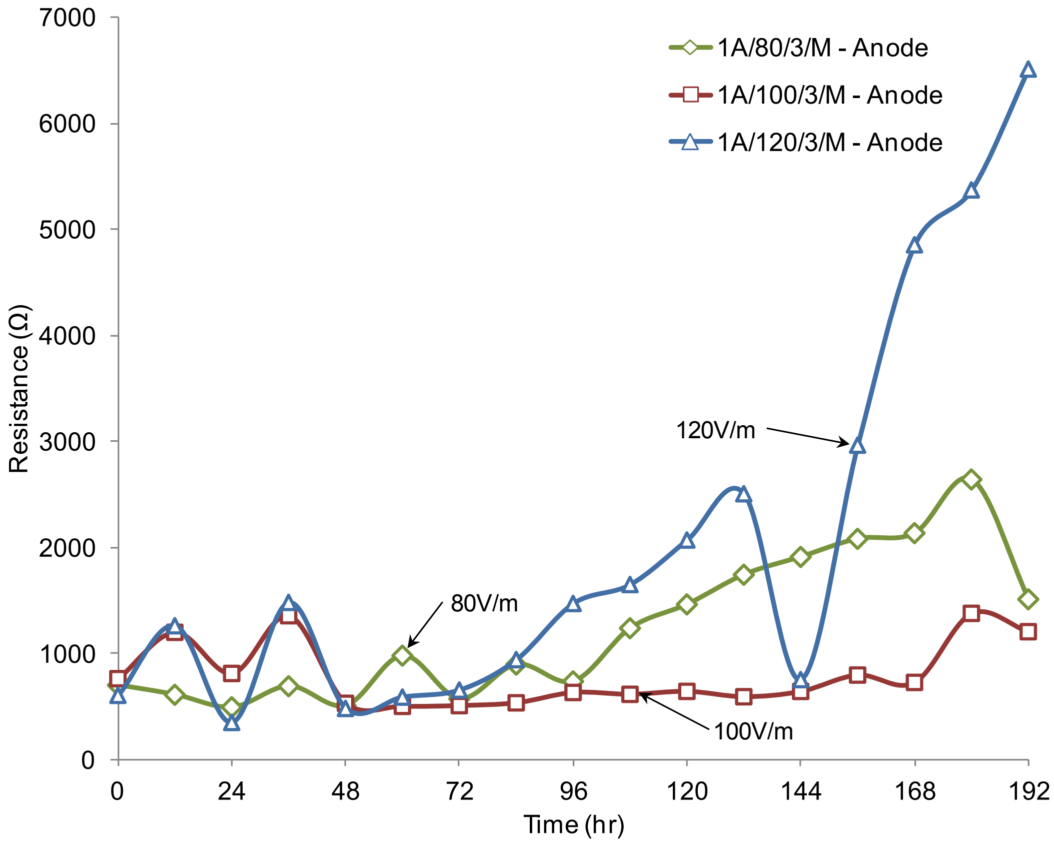
(b)

Figure 4.15: Resistance of middle region in (a) small and (b) large scale EO tests with voltage gradient of 80V/m, 100V/m and 120V/m

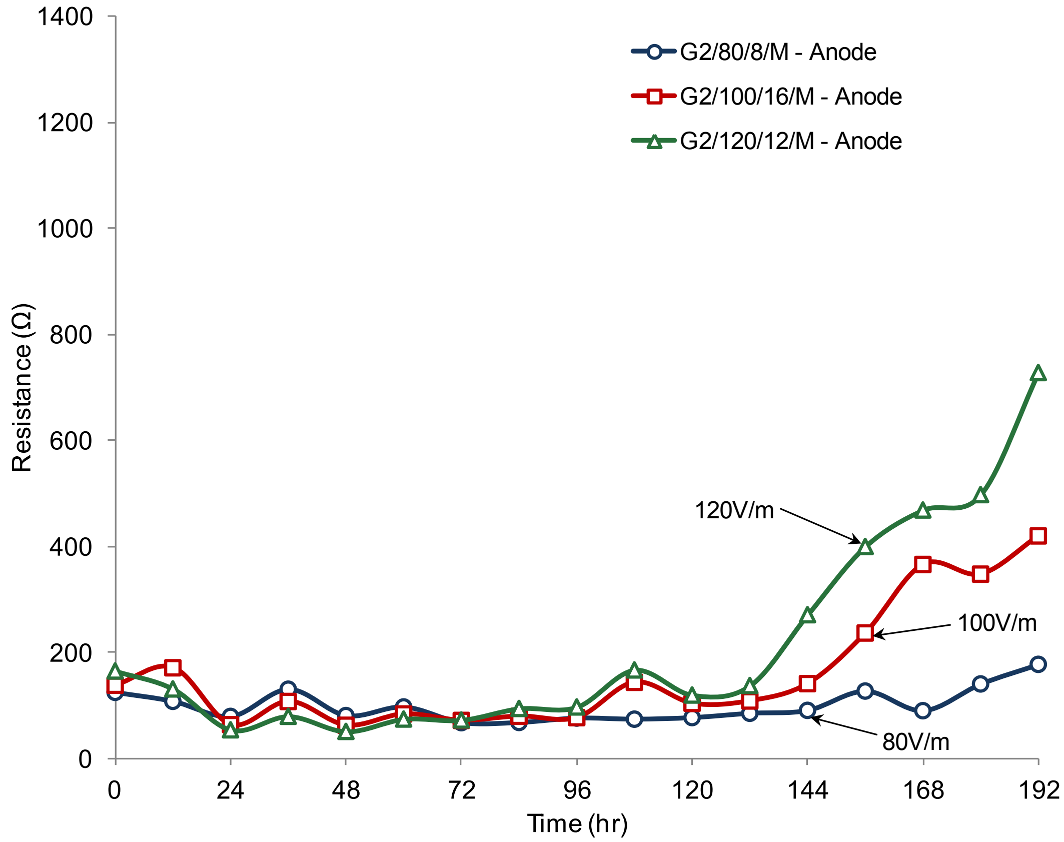
Figure 4.15(a) shows the variation in resistance of the middle region in the small scale EO test. The middle region is located between the first and last voltage probes at 0.16 and 0.84 normalized distances from the cathode. The resistance of the middle region reflects the resistance of peat during EO test. Initial resistance of the middle region is 348Ω, 404Ω and 382Ω for test with 80V/m, 100V/m and 120V/m respectively. The resistance of the peat between the first and last voltage probes does not show significant trends during the small scale EO tests. For the test with voltage gradient of 80V/m, resistance ranges from 348 to 654Ω. For the test with voltage gradient of 100V/m, resistance ranges from 394 to 571Ω. For the test with voltage gradient of 120V/m, resistance ranges from 382 to 524Ω. The resistance of the peat appears not to be affected by the different applied voltage gradient as all three small scale EO tests show similar range of resistance, as seen in Figure 4.15(a).

Figure 4.15(b) shows the variation in resistance of the middle region between H1-H4 of the large scale EO test. The resistance of the middle region between the second pair of electrodes is shown as Appendix A 5. For the large scale EO tests, initial resistance of the middle region is 83Ω, 65Ω and 86Ω for test with 80V/m, 100V/m and 120V/m respectively. In the large scale EO tests, the resistance of the middle region show gradual increase with time. For the test with voltage gradient of 80V/m, resistance of the middle region ranges from 83 to 304Ω. In the test with voltage gradient of 100V/m, resistance of the middle region ranges from 65 to 220Ω. With voltage gradient of 120V/m, resistance of the middle region ranges from 86 to 286Ω.

In the small scale EO tests, resistance of the middle region range from 348 to 654Ω. In the large scale EO tests, resistance of the middle region range from 36 to 332Ω (for both sets of electrodes). The resistance of the middle region shows comparatively lower magnitude compared to the resistance of the cathode region. No large increment in resistance is observed for the small and large scale EO tests. The increase in resistance of the middle region might be attributed to the removal of water and reduction in conductivity. As gas generation is limited to the vicinity of the electrodes, the middle region is not affected by increase in resistance due to gas generation, hence the lower resistance compared to that of the cathode.



(a)



(b)

Figure 4.16: Resistance of anode region in (a) small and (b) large scale EO tests with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.16(a) shows the variation in resistance of the anode region in the small scale EO tests. The anode region is the area between the last voltage probe at 0.84 normalized distance (from cathode) and the anode. Initial resistance of the anode region is 696Ω, 757Ω and 600Ω for test with 80V/m, 100V/m and 120V/m respectively. The initial resistance of the anode region shows similar range to the initial resistance of the cathode region of the same test. In the initial stage, larger fluctuations are observed in the tests with voltage gradient of 100V/m and 120V/m. From 72hr onward, an increasing trend can be observed in all three tests. Test with voltage gradient of 100V/m shows the lowest increment while test with voltage gradient of 120V/m shows the highest increment. Maximum resistance is 2639Ω, 1374Ω and 6514Ω for voltage gradient of 80V/m, 100V/m and 120V/m respectively. The lower resistance of the anode region in test with voltage gradient of 100V/m might be due to trapped water in the void near the anode. The presence of trapped water might increase conductivity of peat in its vicinity and at the same time lower resistance.

As for the test with voltage gradient of 120V/m, the large increment in resistance could be a result of the development of the crack between the last voltage probe and the anode. As the crack increased in width and depth, the current transmitted through the peat is greatly reduced. In the same test, a low resistance value of 749Ω is recorded at 144hr. For the same time (144hr), resistance of the cathode region only show a slight reduction while no reduction is observed in the resistance of the middle region. Only the resistance of the anode region exhibited large reduction in resistance at 144hr. This is a possible indication that water is trapped in the vicinity of the anode, causing a short circuit in the electrical system as discussed earlier.

Figure 4.16(b) shows the resistance of the anode region along H1-H4 of the large scale EO tests. The resistance of the anode region along L1-L4 is shown as Appendix A 6. Initial resistance of the anode region is 124Ω, 137Ω and 164Ω for test with 80V/m, 100V/m and 120V/m respectively. Resistance of the anode region for all three tests only show a slight reduction at the early stage of the test. Increase in resistance is observed from 96hr onward with highest increment in the test with voltage gradient of 120V/m. Maximum resistance of the anode region is 177Ω, 419Ω and 727Ω for test with voltage gradient of 80V/m, 100V/m and 120V/m respectively.

By separating the resistance into three sections, namely the cathode, middle and anode region, the variation in resistance between the electrodes can be studied. From the data presented, main resistance of the electrical system is located in the vicinity of the cathode and anode, in other words the area around the electrodes. The resistance of peat (middle region) shows relatively lower resistance compared to that of the electrodes. Resistance of peat ranges from 350 to 650Ω in the small and large scale EO tests with no significant increment. Resistance of the anode region shows higher increment compared to that of the cathode region. This could due to the movement (EO flow) of water away from the anode. Casagrande (1949) stated that the drying process increased resistivity of the soil. Test results are in agreement with Casagrande's statement with regards to increase in overall resistance of the electrical system. In addition to that, gas generation at the electrodes could further increase resistance near the electrode (Mitchell and Soga, 2005). Higher volume of water removed, coupled with gas generation could lead to the highest resistance observed near the anode.

In the large scale EO test, the resistance at the cathode region is generally higher than that of the anode region. The lower resistance at the anode region of the large scale test is attributed to the absence of drainage well at the anode. Without the drainage well, the anode is in direct contact with the peat, increasing voltage transmitted. This is reflected in the lower voltage losses near the anode of the large scale test, seen in Figure 4.16(b), as compared to that of the small scale test. Lefebvre and Burnotte (2002) found that voltage loss at the anode is related to the resistance of the area in the vicinity of the anode. The overall lower resistance of the large scale tests might also be due to the wider 30mm electrodes used compared to the 15mm wide electrodes used in the small scale test. With larger widths, the surface area of the electrodes is increased which could lead to higher soil-electrode contact and lower resistance.

4.2.5 Moisture content and pH of peat after EO tests

Table 4.1 below presents the final moisture content obtained at three different locations for the small scale EO tests with voltage gradient of 80V/m, 100V/m and 120V/m. Final moisture content was obtained from the soil sample collected in Shelby tubes at 7cm, 12.5cm and 18cm from the cathode. The peat sample extruded from the Shelby tube was separated into segments to study the final moisture content at different depths. The final moisture contents of the large scale EO tests are not presented due to variation in test durations.

In the test with voltage gradient of 80V/m, initial moisture content was 592%. Final moisture contents range from 338 to 385% with lower final moisture content near the anode and higher final moisture content near the anode. For the test with voltage gradient of 100V/m, initial moisture content was 549%. Final moisture content ranges from 288 to 381%. The initial moisture content for test with voltage gradient of 120V/m was 564%. The final moisture contents range from 331 to 369%. Both the tests with voltage gradient of 100V/m and 120V/m also exhibit lower final moisture content near the anode and higher final moisture content near the cathode.

To gauge the degree of reduction in moisture content, percentage of reduction in moisture content is also presented in Table 4.1. The percentage of reduction in moisture content was calculated as the percentage of change in moisture content over the initial water content. In the test with voltage gradient of 80V/m, the percentage of reduction in moisture content at 7cm from the cathode ranges from 34.9 to 36.6%. At 12.5cm away from the cathode, reduction in moisture content is between 37.8 to 42.9%. At 18cm away from the cathode, reduction in moisture content is from 42.4 to 42.7%. Highest reductions are observed at the middle of the tank and in the vicinity of the anode.

For the test with voltage gradient of 100V/m, the percentage of moisture content reduction at near the cathode ranges from 41.5 to 43.1%. At the middle of the test bed, the percentage in reduction of moisture content ranges from 30.6 to 47.5%. At 18cm away from the cathode, near the anode region, percentage of reduction in moisture content is from 43 to 44.8%. The relatively lower reduction in moisture content near the electrodes at the bottom of the test sample is indicative of the trapped water in the test with voltage gradient of 100V/m.

With applied 120V/m, the percentage of reduction in moisture content at 7cm away from the cathode ranges from 34.5 to 37.6%. At 12.5cm away from the cathode, the percentage of reduction in moisture content is between 39.3 to 41.3%. At 18cm away from the cathode, percentage of reduction in moisture content is 39.0% and 41.3%. Higher reduction at the middle of the test tank and in the vicinity of the anode is also observed in the test with 120V/m.

All three small scale EO tests show higher reduction in moisture content near the anode than the cathode. This trend of higher moisture content reduction near the anode and lower moisture content reduction near the cathode indicates the direction of EO flow. In this case, the main EO flow is from the anode toward the cathode, reflected in the final moisture content and reduction in moisture content data. All three EO tests show reduction in moisture content higher than 30%. Maximum percentages of reduction in moisture content are 42.9%, 47.5% and 41.3% respectively for test with voltage gradient of 80V/m, 100V/m and 120V/m. Test with voltage gradient of 100V/m shows the highest overall reduction in moisture content.

Table 4.1: Comparison of final moisture content post EO test of peat with applied voltage of 80V/m, 100V/m and 120V/m

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
1A/80/3/M	592	385	355	339	34.9	40.0	42.7	0 - 3 cm
		381	339	341	35.6	42.7	42.4	3 - 6 cm
		375	338	341	36.6	42.9	42.4	6 - 9 cm
		-	368	-	-	37.8	-	9 - 12 cm
1A/100/3/M	549	312	289	313	43.1	47.3	43.0	0 - 3 cm
		317	300	311	42.2	45.3	43.3	3 - 6 cm
		321	288	304	41.5	47.5	44.6	6 - 9 cm
		-	381	303	-	30.6	44.8	9 - 12 cm
1A/120/3/M	564	369	342	331	34.5	39.3	41.3	0 - 3 cm
		355	335	344	37.0	40.6	39.0	3 - 6 cm
		352	331	-	37.6	41.3	-	6 - 9 cm

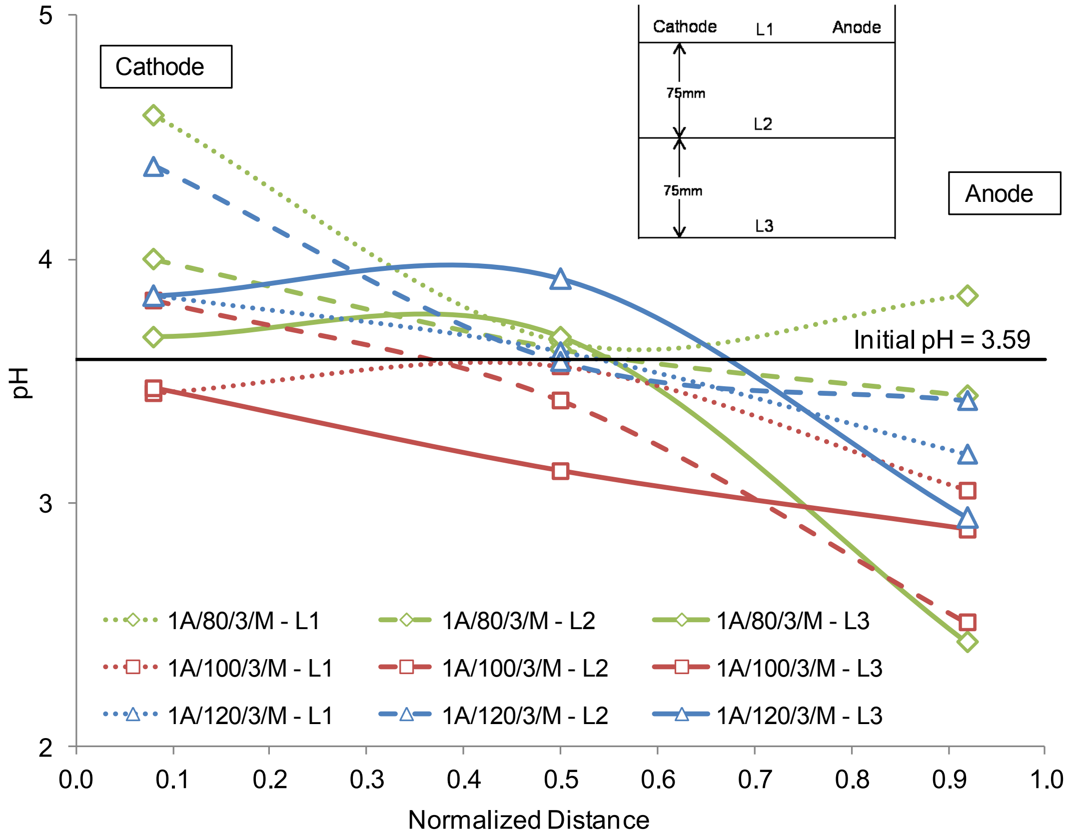


Figure 4.17: pH of peat after small scale EO test with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.17 shows the pH of peat at the end of the small scale EO test. Soil samples were obtained near the cathode and anode as well as the middle of the test bed. For each location, a sample was collected from the top (L1), middle (L2) and bottom (L3) of the peat specimen. This was done to gauge the changes in pH with depth between the cathode and the anode. Initial pH of the peat was 3.59. The electrolysis reactions at the electrodes are evident with the changes in pH of peat. Production of hydrogen ions, H^+, at the anode decreased the pH in the peat at the vicinity of the anode. At the cathode, hydroxide ions, OH^-, generated increased the pH of peat in the vicinity of the cathode.

In the test with voltage gradient of 80V/m, the final pH values range from 2.43 to 4.59. It can be observed that the pH values near the cathode have increased from initial value of 3.59. However, the middle of the test tank shows only marginal increase in pH values. Near the anode, pH has significantly dropped at the bottom (L3) of the test bed. The middle (L2) layer shows only a slight reduction in pH while the top layer (L1) exhibited a slight increase in pH.

In the test with voltage gradient of 100V/m, final pH of the peat ranges from 2.51 to 3.83. The pH values near cathode for the test with voltage gradient of 100V/m show the lowest increment among the three tests. The pH values are also the lowest at the middle and near the anode among the three tests. All measured pH are lower than initial pH of 3.59, with only pH near the cathode at L2 showing an increase to 3.83.

With voltage gradient of 120V/m, the final pH of peat range from 2.94 to 4.38. At the middle of the test bed, only pH of the bottom layer (L3) shows increase while the middle and top layer show no significant difference to initial pH. Reduction in pH values near the anode is seen for all three layers (L1, L2 and L3) of the peat. The reduction in pH of the test with voltage gradient of 120V/m is less than that of the test with voltage gradient of 100V/m.

For the small scale EO tests, the pH of water collected was measured when the volume of water was 50mℓ or more. In the test with 80V/m, pH of the water collected ranges from 10.29 to 11.64. For the 100V/m test, pH of the water collected ranges from 9.60 to 10.65. pH of the water collected in the 120V/m test ranges from 10.18 to 11.67. While the pH of the water collected is high, pH of the peat in all 3 tests do not exhibit large reduction or increment at the end of the test. This is attributed to the high buffer capacity of peat. Initial pH of peat is 3.59 and lowest recorded pH is 2.43 and highest recorded pH is 4.59 in the test with 80V/m. Asadi *et al.*, 2009 reported that the iso-electric point of organic soil ranges between pH 2.5 – 3.5, where the EO flow ceases as zeta potential, ξ, approaches 0mV. However, from Figure 4.7(a), it can be seen that EO flow in all 3 tests did not cease throughout the test duration. Hence EO flow continues to occur in peat at when pH is lower than 2.5.

4.2.6 Undrained shear strength of peat after EO tests

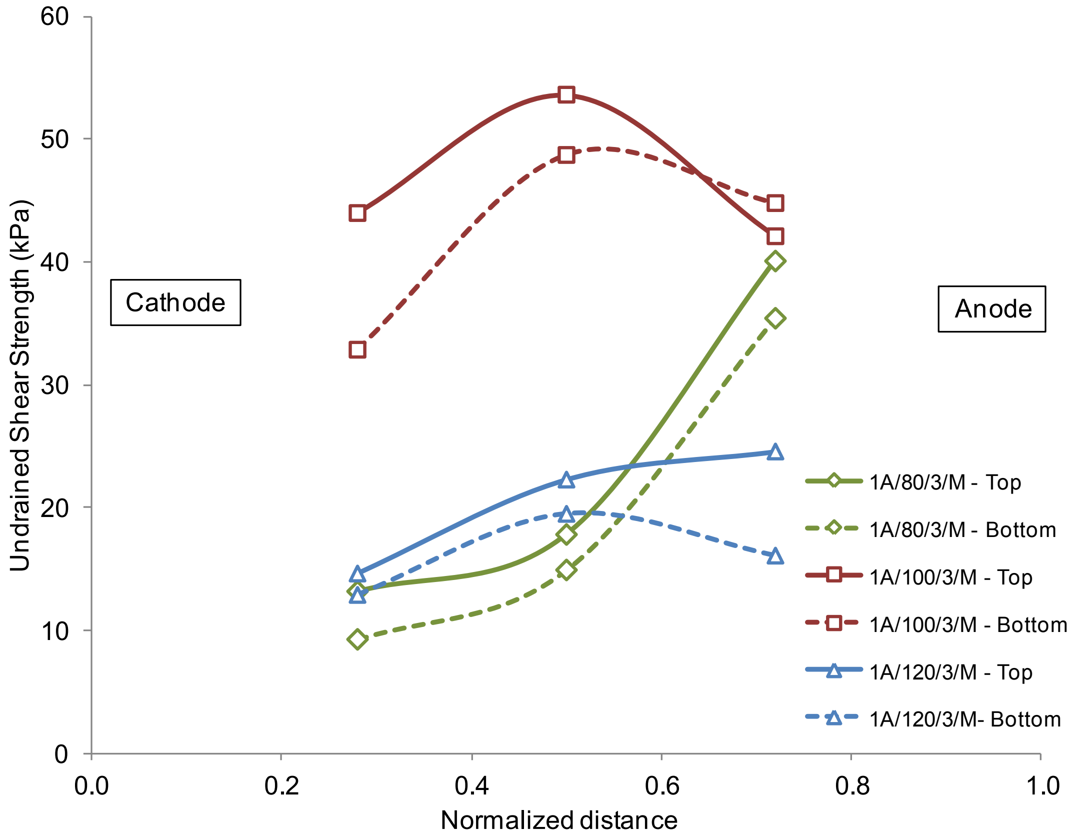


Figure 4.18: Final undrained shear strength of small scale EO test of peat with voltage gradient of 80V/m, 100V/m and 120V/m

Figure 4.18 shows the undrained shear strength at the top and bottom of the peat at the end of the small scale EO test. The final undrained shear strength of the large scale tests are not presented due to difference in test durations. For the small scale test, three different locations were chosen for the laboratory vane shear test. The locations were 0.28, 0.5 and 0.72 normalized distances from the cathode. Initial undrained shear strength was 1.71kPa, 0.93kPa and 1.99kPa for test with 80V/m, 100V/m and 120V/m respectively.

All three tests show similar undrained shear strength trends at the top and bottom of the peat. For the test with voltage gradient of 80V/m, final undrained shear strength ranges from 9 to 40kPa. In this test, the area near the anode underwent the highest strength gain. With voltage gradient of 100V/m, final undrained shear strength ranges from 33 to 54kPa and maximum is at the middle region. With the small scale test, water was observed to have a tendency to accumulate in the vicinity of the electrodes. This would mean that it could be possible for some of the trapped water to be reabsorbed. This in turn results in lower moisture content reduction and lower strength gain. As a result, the strength near the anode and cathode is lower than that of the middle region, which is evident in the test with voltage gradient of 100V/m. In the test with voltage gradient of 120V/m, final undrained shear strength ranges from 13 to 24kPa.

The test with voltage gradient of 120V/m shows the lowest strength gain while the test with voltage gradient of 100V/m shows the highest overall strength gain. Highest undrained shear strength is 54kPa or 5706% increase observed in the test with voltage gradient of 100V/m. The final undrained shear strength in the test with 120V/m show little improvement over the final undrained shear strength in the test with 80V/m. This could be due to the development of large cracks in the test with voltage gradient of 120V/m, discussed earlier (Figure 4.4).

The undrained shear strength increase is attributed to reduction in moisture content, leading to consolidation and decrease of void ratio. Higher moisture content reduction resulted in higher settlement as well as higher strength gain. The higher undrained shear strength is attributed to pH changes near the anode (Asadi *et al.* 2009 and Asadi *et al.* 2010). With the application of DC, electrolysis of water occurs at the electrodes. In the vicinity of the anode, H^+ ions are generated. An increased in H^+ ions reduces the pH of the soil. At the same time, the H^+ neutralizes the negative charges in zeta potential, ξ. With the reduction of ξ, the diffused double layer also decreases, resulting in less repulsive forces between the organic particles. The reduction in repulsive forces in turn causes the organic particles to aggregate, forming larger particles. Lower shear strength improvement at the cathode is attributed to higher ξ near cathode (Asadi *et al.* 2010). Electrolysis causes OH^- ions to be produced and this contributes to the negative charges of the organic particles, leading to higher ξ. At higher ξ, the diffused double layer increases, resulting in higher repulsive forces between organic particles.

4.3 Effect of incremental voltage gradient on EO of organic soil and peat

Tests with fixed and incremental voltage gradients were carried out on organic soil and peat. Applied voltage gradient was fixed voltage gradient of 80V/m and incremental voltage gradient of 10~80V/m, averaging to 45V/m for eight days.

Control tests without application of DC were also included for organic soil and peat. For the tests with organic soil, initial moisture content of the organic soil was 302%, 306% and 287% for control test, fixed 80V/m and incremental voltage respectively. Initial undrained shear strength of the organic soil was 0.92kPa, 1.19kPa and 0.92kPa for control test, fixed 80V/m and incremental voltage respectively. In the tests with peat, initial moisture content of the control, fixed 80V/m and incremental voltage test was 663%, 654% and 628% respectively. Initial undrained shear strength was 0.92kPa, 1.05kPa and 1.19kPa for control test, fixed 80V/m and incremental voltage respectively. Further details of the test series can be found in Table 3.1. Figure 4.19 shows the layout of the small scale EO tests with fixed and incremental voltage gradient.

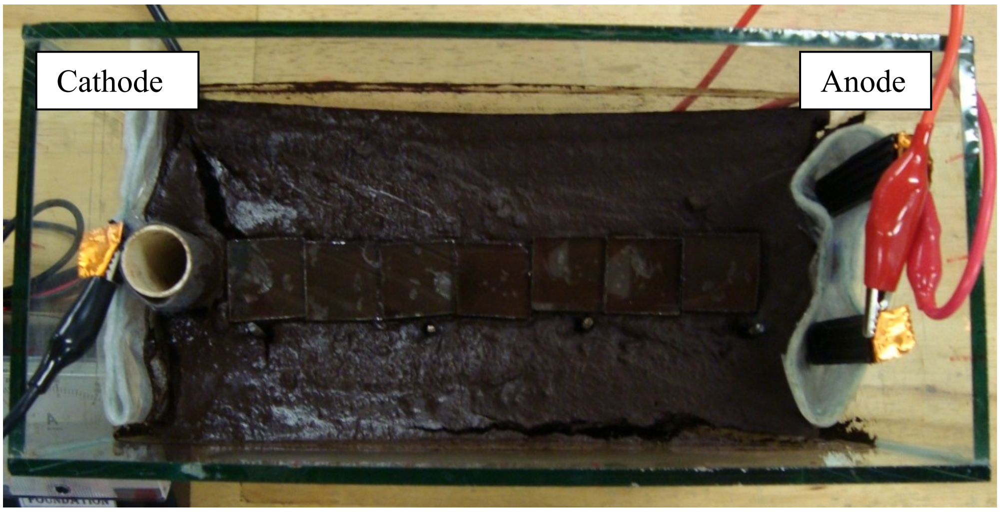


Figure 4.19: Plan view of small scale EO tests with fixed and incremental voltage gradient

4.3.1 Settlement profile of organic soil and peat during EO tests

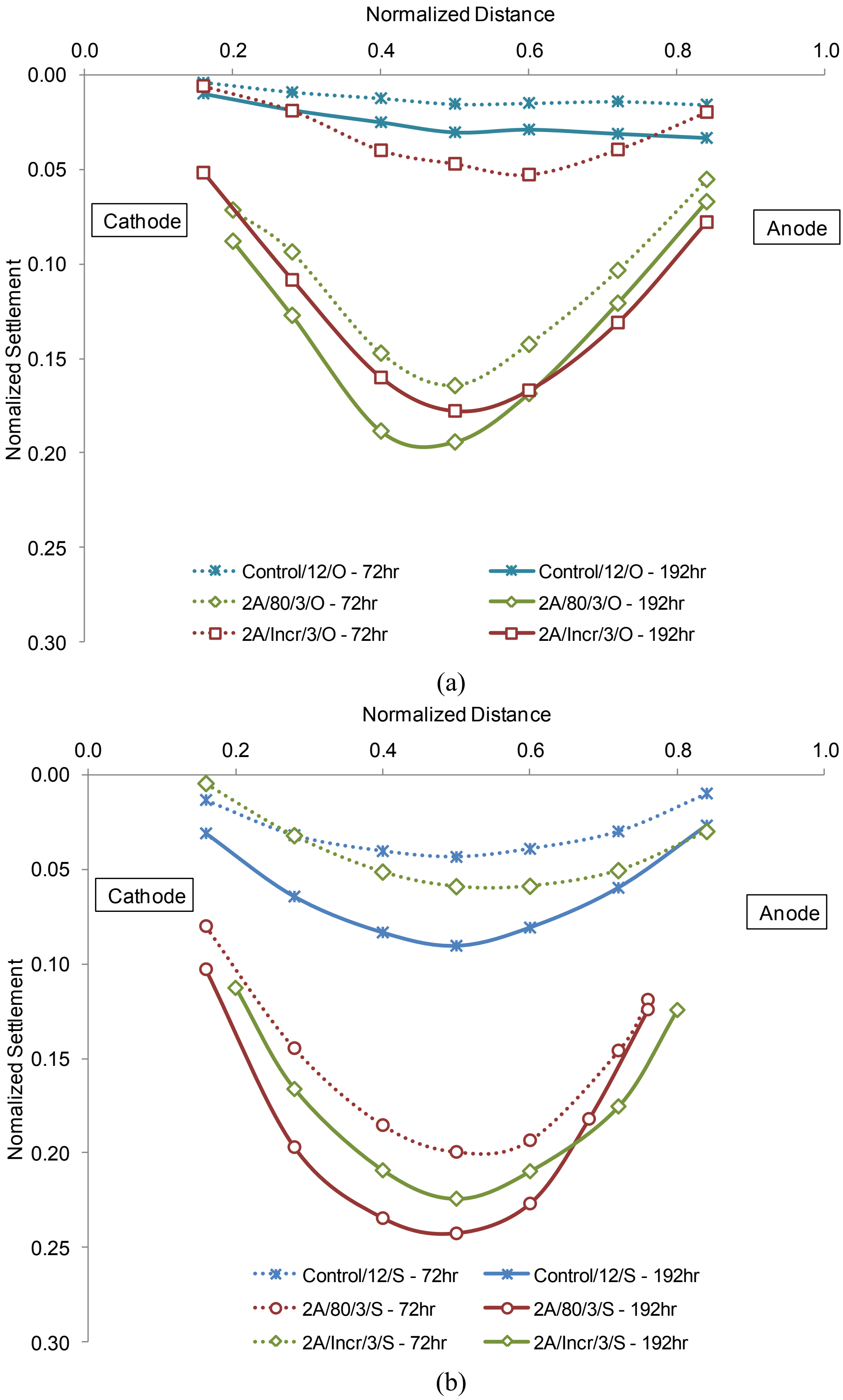


Figure 4.20: Normalized settlement profile of (a) organic soil and (b) peat during EO tests with fixed 80V/m and incremental voltage gradient

Figure 4.20(a) shows the normalized settlement profile of organic soil with time during EO tests with fixed 80V/m and incremental voltage gradient. Settlement profile of the control test is also included. Measured settlement is normalized using the initial height of the organic soil, 200mm. In the control test, settlement under self-weight condition occurs at a significantly lower rate compared to tests with EO. EO greatly expedited the settlement of organic soil. At the end of the test, the maximum normalized settlement of the control test is only 0.03 or 3%.

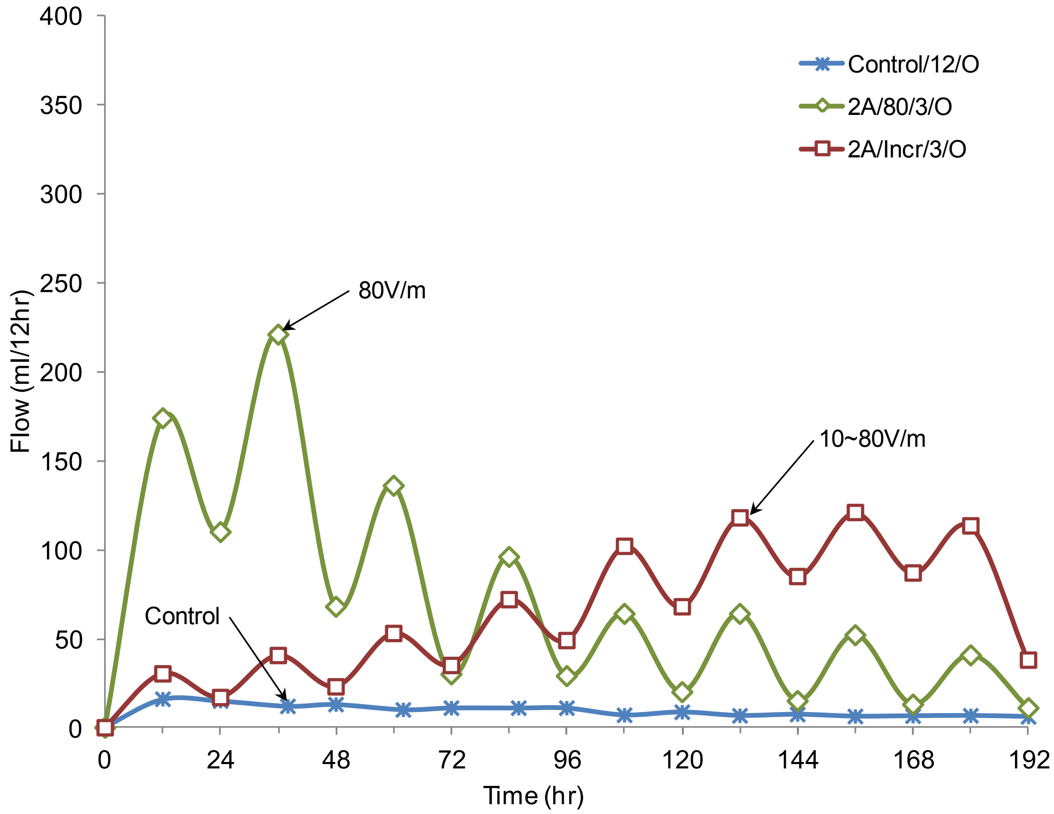
After 72hr of the application of DC, test with fixed 80V/m shows the highest settlement. Maximum normalized settlement is 0.16 at the middle of the test bed. In the test with incremental voltage, rate of settlement is visibly lower in the early stages of the test. At the end of the test, maximum normalized settlement in the test with fixed 80V/m is 0.19. From 72hr to 192hr, the maximum normalized settlement has only increased by 0.03. In the test with incremental voltage, the rate of settlement increases with time. This is due to the increment of voltage gradient with time. At 192hr, maximum normalized settlement in the test with incremental voltage is 0.18 at 0.5 normalized distance from the cathode. Although the average voltage gradient of 45V/m of the incremental voltage test is lower than the test with fixed 80V/m, the difference between the maximum normalized settlement of fixed 80V/m and incremental voltage gradient is only 0.02 or 2%.

Figure 4.20(b) shows the normalized settlement profile of peat in EO test with fixed 80V/m and incremental voltage gradient. For the control test, rate of settlement of peat under self-weight condition is the lowest among the three tests. After eight days, maximum normalized settlement of the control test is 0.09 or 9%. Settlement of test with fixed voltage gradient of 80V/m is the largest at 72hr at 0.2 or 20%. For the same duration, the test with incremental voltage shows a very low rate of settlement with maximum of 0.06 at 72hr. At the end of the test, largest normalized settlement is observed in the test with fixed voltage gradient of 80V/m. Maximum normalized settlement is 0.24 and 0.22 for fixed 80V/m and incremental voltage gradient respectively. The difference between the maximum normalized settlement of fixed 80V/m and incremental voltage at 192hr is approximately 0.02 or 2%.

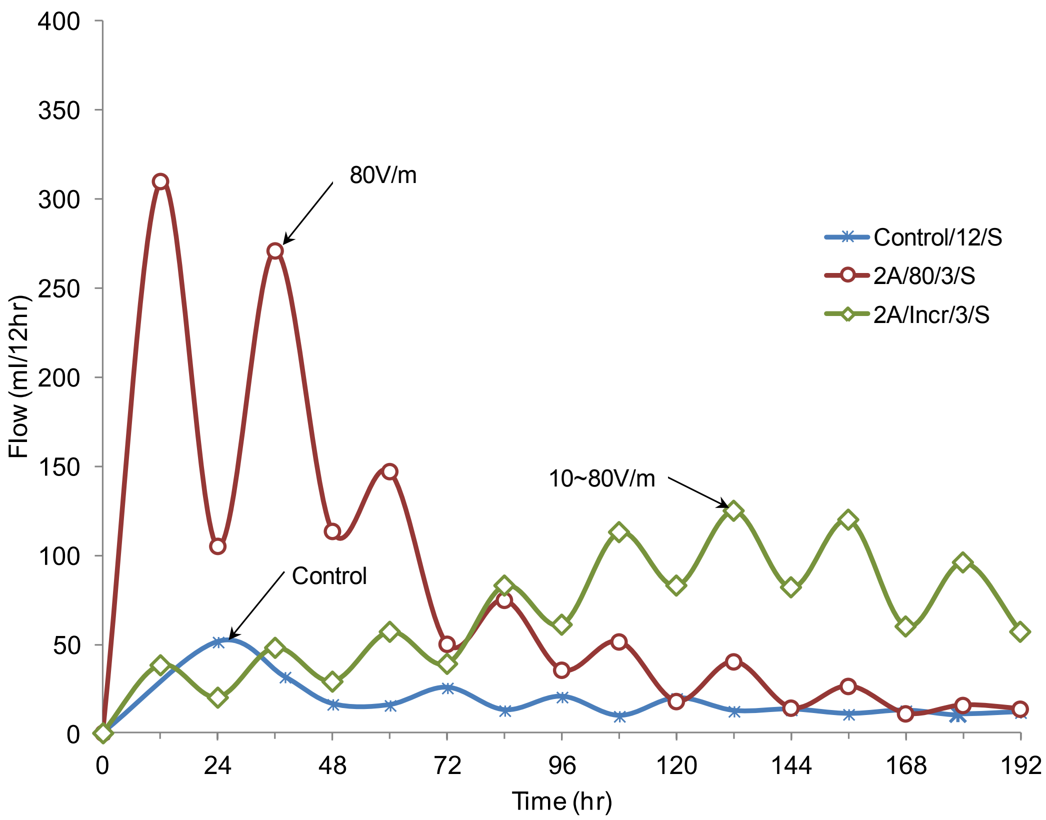
In the test with organic soil, it is observed that in the test with fixed voltage gradient, more than 80% of the final settlement occurred within 72hr of the test. For the same period of time, in the test with incremental voltage gradient, only 28% of the final settlement is achieved. In the test with peat, a similar trend is also observed, with 83% of the final settlement occurring within 72hr of the test with fixed voltage gradient of 80V/m. This implies that at 72hr of the tests with incremental voltage gradient, applied voltage gradient lower than 30V/m did not induce significantly larger settlement in organic soil and peat as compared to the control tests.

Comparing the normalized settlement of organic soil and peat, larger overall normalized settlement is observed in peat. Maximum normalized settlement in organic soil at 80V/m is 0.19 while maximum normalized settlement for peat is 0.24. For the test with incremental voltage, the maximum normalized settlement in organic soil and peat is 0.18 and 0.22 respectively. The higher normalized settlement in peat reflects the higher compressibility of peat.

4.3.2 Water collected during EO of organic soil and peat



(a)



(b)

Figure 4.21: Average flow during EO test on (a) organic soil and (b) peat with fixed 80V/m and incremental voltage gradient

Figure 4.21(a) shows the average flow of water collected from the drainage well during EO test in organic soil. Flow of water is plotted over 12-hour intervals. In the control test, initial average flow is 16mℓ/12hr and 15mℓ/12hr at 12hr and 24hr respectively. Flow in the control test is due to the hydraulic gradient of the organic soil and is the lowest among the three tests.

For the test with fixed 80V/m, application of DC greatly expedited flow in organic soil. The average flow at 12hr and 24hr is 174mℓ/12hr and 110mℓ/12hr respectively. The average flow shows increase on the second day. Average flow at 36hr and 48hr is 221mℓ/12hr and 68mℓ/12hr respectively. Following that, a gradual decline in flow with time is observed.

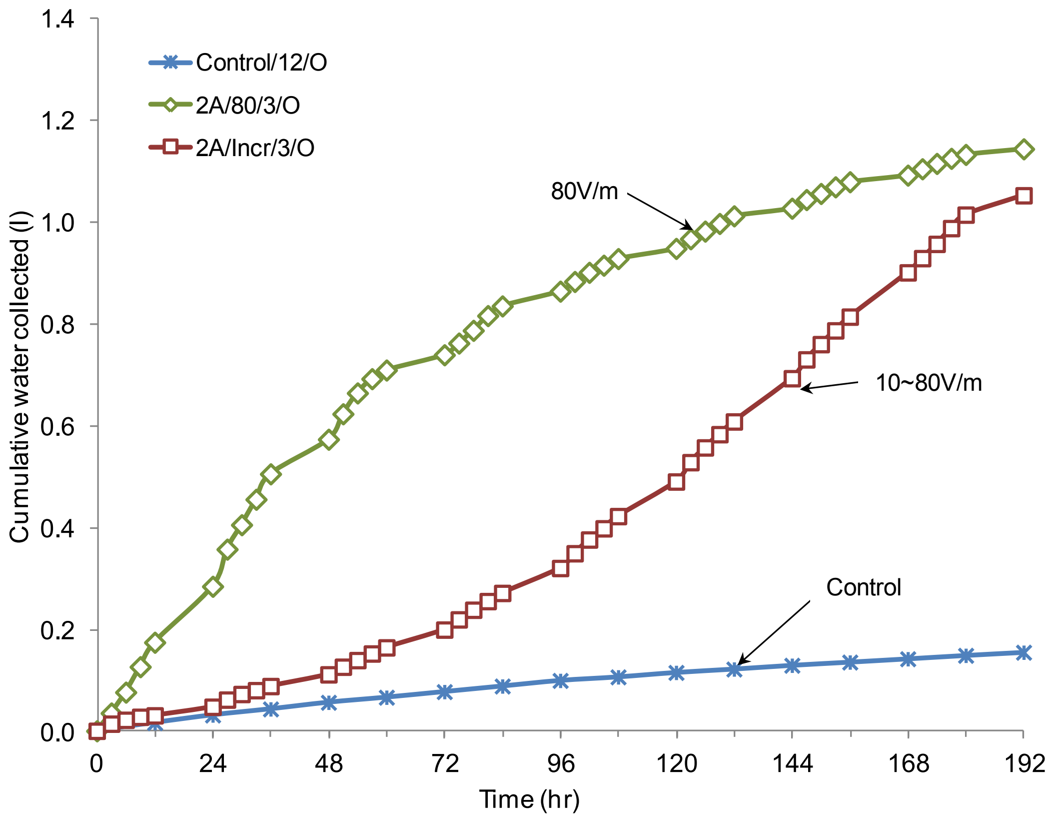
In the first 24 hours of the test with incremental voltage, the voltage gradient was 10V/m. The resulting flow is only marginally higher than the flow in the control test. Average flow for 12hr and 24hr is 30mℓ/12hr and 17mℓ/12hr respectively. The average flow per day is 47mℓ/day, which is slightly higher than average flow of 31mℓ/day for the same period of time of the control test. With each increment in voltage gradient, the average flow also shows increase. The average flow in the incremental voltage gradient test peaks at 156hr with 121mℓ/12hr. Following this, a decline in flow rate is observed. Highest average flow per day is recorded as 208mℓ/day at Day 7.

Figure 4.21(b) shows the average flow of water collected during EO tests on peat. Flow in the control test is plotted at 24-hour intervals as the water in the drainage well was removed at 24-hour intervals. Similar to tests on organic soil, control test on peat also shows the lowest flow. At 24hr, the average flow is 51mℓ/day, while at 48hr, the average flow is 48mℓ/day. As observed in the control test on organic soil, the control test on peat also shows declining average flow with time.

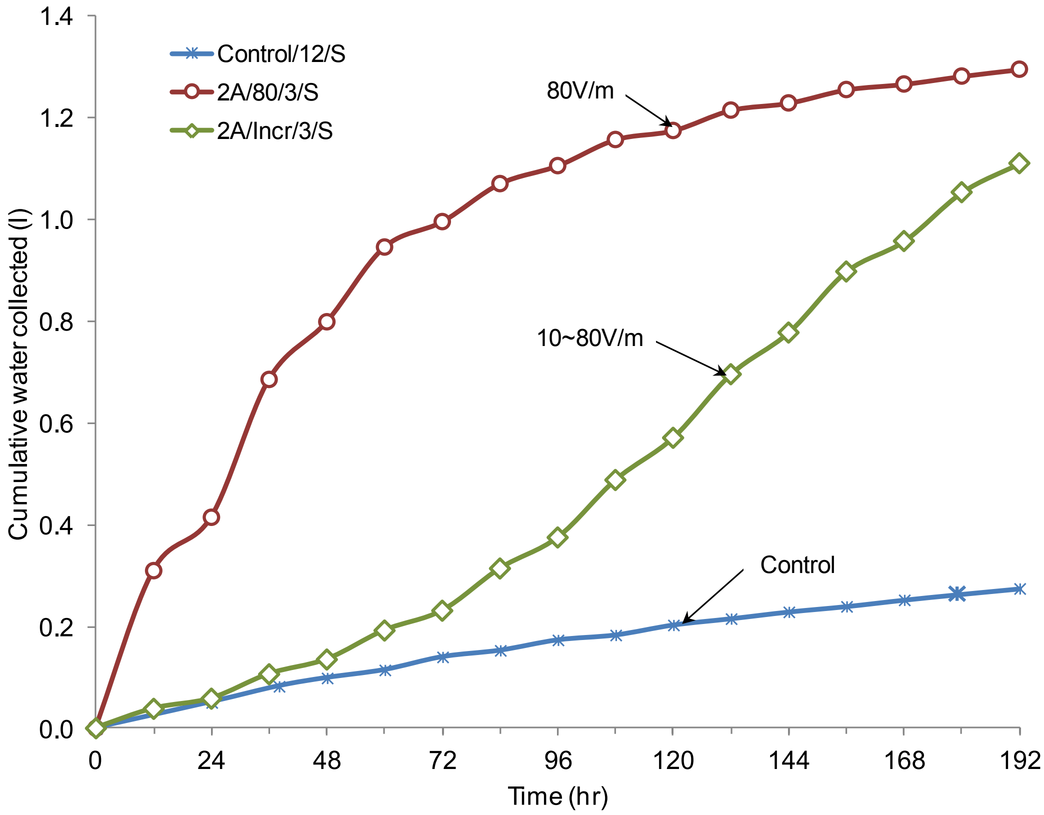
For the test with fixed voltage gradient of 80V/m, highest average flow occurred in the first 12 hours of the test with 310mℓ/12hr. Following that, the flow shows gradual reduction with time. The trend in flow in peat is similar to that in organic soil earlier, with higher flow recorded for the first two days of testing (Asadi *et al.*, 2010) and in kaolinite (Eykholt and Daniel, 1994). On the first two days of the test on peat, the average flow per day in test with fixed 80V/m is higher than that of the organic soil. However from Day 3 onward, average flow in peat is lower than that in organic soil. This might be due to the higher rate of water removed from peat in the first two days. This results in a drier region in the vicinity of the anode which leads to reduced conductivity.

The test with incremental voltage on peat shows low initial flow which is similar to that of the control test. This might be due to the low initial voltage gradient of 10V/m, where the current generated in peat too low to create an electro-osmotic driving force. Similar low flow is also seen at the early stages of the test with incremental voltage in organic soil. However, the low initial EO flow is more apparent in peat where little difference is observed between the flow at applied 10V/m and 20V/m and the flow in the control test. At 48hr, the applied voltage gradient was increased to 30V/m. With this increment in voltage gradient, the EO flow in peat shows a higher increase in flow. This implies that a minimum applied voltage gradient of 30V/m might be required to induce reasonable EO flow in peat. Highest average flow is recorded at 132hr with 125mℓ/12hr and peak flow is recorded as 207mℓ/day on Day 6. After that, the EO flow starts to show reduction with time.

From the tests with incremental voltage gradient, it can be observed that higher voltage gradient results in higher flow in organic soil and peat. With stepped increment in voltage gradient, the peak flow normally observed at the early stages of the test with fixed voltage gradient is not observed. Highest flow for the test with incremental voltage gradient occurs at the later stage of the test. Low flow at the early stages of the test in organic soil and peat might signify that the current transmitted is too low to induce reasonable EO flow. Similar condition was observed in the field trial on marine clay by Chew *et al*. (2004). Initial voltage gradient of 25V/m during the field trial did not induce flow. Flow was only observed after the voltage gradient was increased to 100V/m.



(a)



(b)

Figure 4.22: Cumulative water collected during EO test on (a) organic soil and (b) peat with fixed 80V/m and incremental voltage gradient

Figure 4.22(a) shows the cumulative water collected during EO test on organic soil. The control test showed the lowest flow and hence the lowest total volume of water collected. Total volume of water collected from the control test is 0.15ℓ. In the test with fixed voltage gradient of 80V/m, 0.57ℓ of water is collected at 72hr. This is half the total volume of water of 1.14ℓ. Higher flow occurred in the first 72 hours of the test. For the test with incremental voltage gradient, total volume of water collected is 1.05ℓ. The total volume of water collected in the incremental voltage gradient test is lower than that of the fixed 80V/m test. This is reflected in the lower settlement of the test with incremental voltage gradient.

With fixed voltage gradient of 80V/m, total volume of water collected is 7.6 times the total volume of water collected in the control test. This indicates that application of DC greatly expedited flow in organic soil. The difference in total volume of water collected from test with fixed 80V/m and incremental voltage is 0.09ℓ. Total volume of water collected from test with fixed 80V/m is 8% higher than that of the test with incremental voltage.

Figure 4.22(b) shows the cumulative water collected during EO test on peat. Total volume of water collected in the control test is 0.27ℓ. In the test with fixed voltage gradient of 80V/m, total volume of water collected is 1.29ℓ. For test with incremental voltage gradient, total volume of water collected is 1.11ℓ. Total volume of water collected in the fixed 80V/m test is 5 times higher than that of the control test. This shows that EO expedited flow in peat. Highest volume of water is in the test with fixed 80V/m. The difference in total volume of water collected from test with fixed 80V/m and incremental voltage gradient is 0.18ℓ or 16%.

In the test with fixed 80V/m and incremental voltage on organic soil, the total volume of water collected is 1.14ℓ and 1.05ℓ respectively. This is similar to the total volume of water collected of 1.29ℓ and 1.11ℓ respectively for test with fixed 80V/m and incremental voltage on peat. All testing conditions were the same for both sets of tests. The only difference was type of soil and initial moisture content. For organic soil, initial moisture content ranged from 287 to 306%. While for peat, initial moisture content was double the initial moisture content of organic soil with values ranging from 628 to 663%.

In the test with fixed 80V/m on peat, the highest flow occurred in the first two days of test followed by a great reduction in flow from 72hr onward. Higher flow in the first two days of test is also recorded in the test with fixed 80V/m on organic soil. However, the reduction of flow in organic soil is slower compared to the reduction of flow in peat. The difference in rate of flow in organic soil and peat could be due to the difference in current generated. This is discussed further later in Section 4.3.3.

4.3.3 Voltage and current in organic soil and peat during EO tests

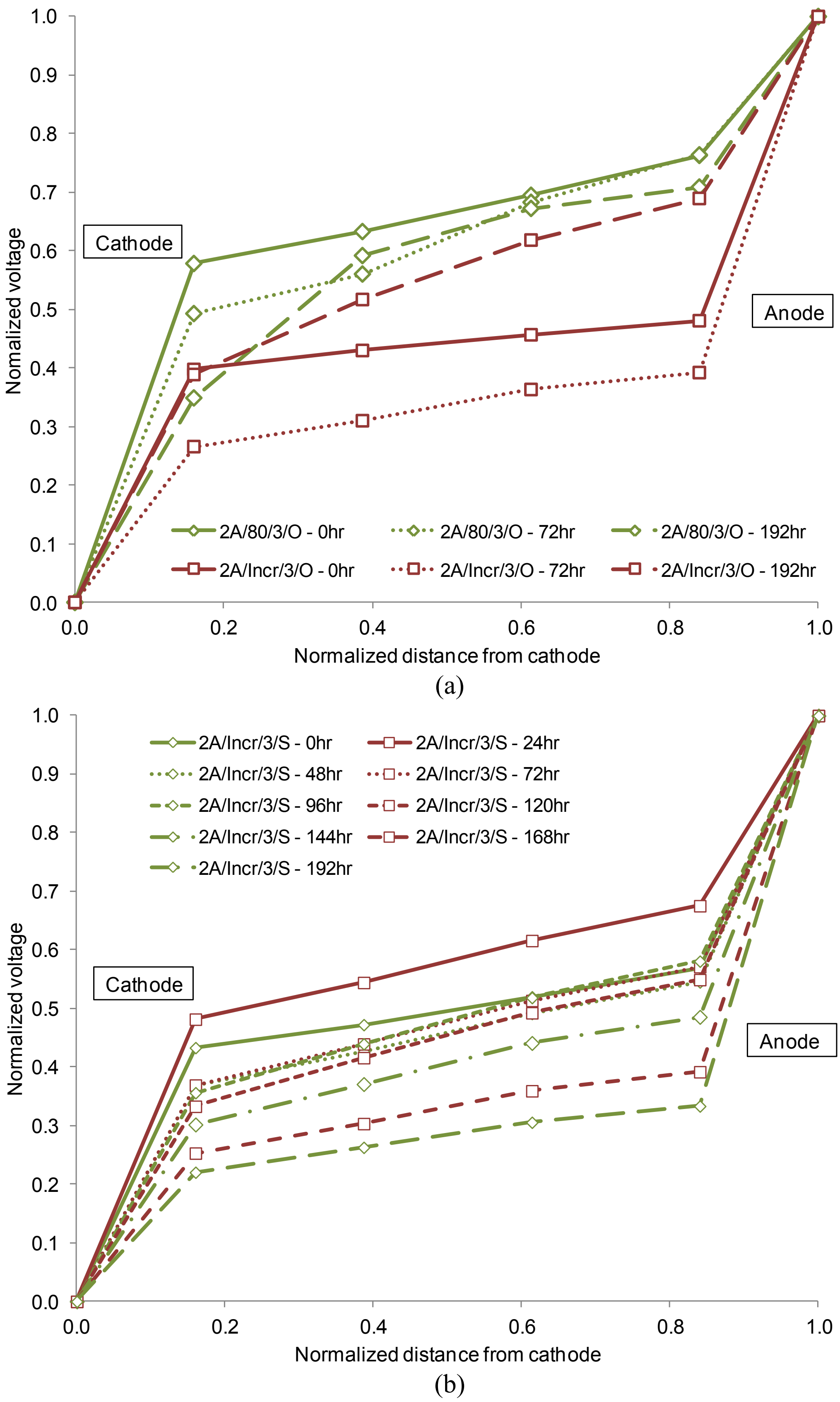


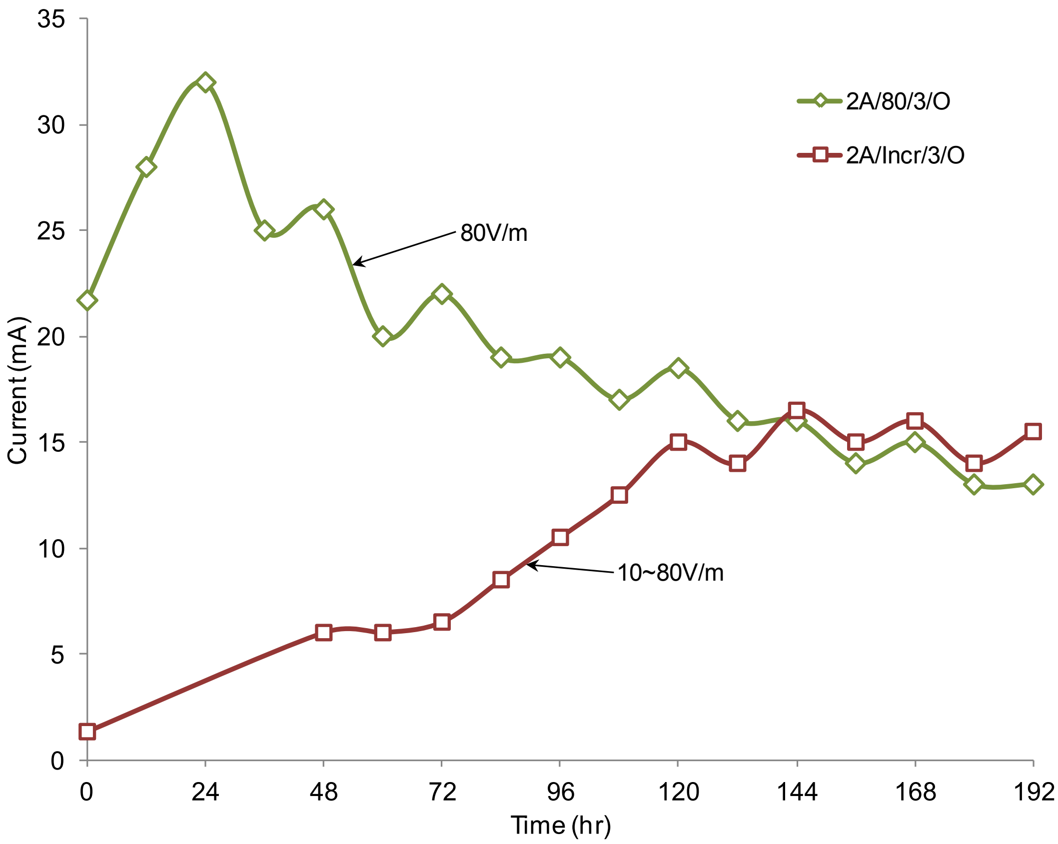
Figure 4.23: Variation of normalized measured voltage in (a) organic soil and (b) peat during EO test with fixed 80V/m and incremental voltage gradient

Figure 4.23(a) shows the variation of measured voltage in organic soil during EO tests with fixed voltage gradient of 80V/m and incremental voltage gradient. The trend of voltage in the organic soil shows similarity to that in peat (Figure 4.23b). Voltage losses in the vicinity of the electrodes are also observed. Similar trend in voltage loss at the cathode and anode was also observed during EO consolidation of clay as reported by Bjerrum *et al.* (1967) and Lo *et al*. (1991).

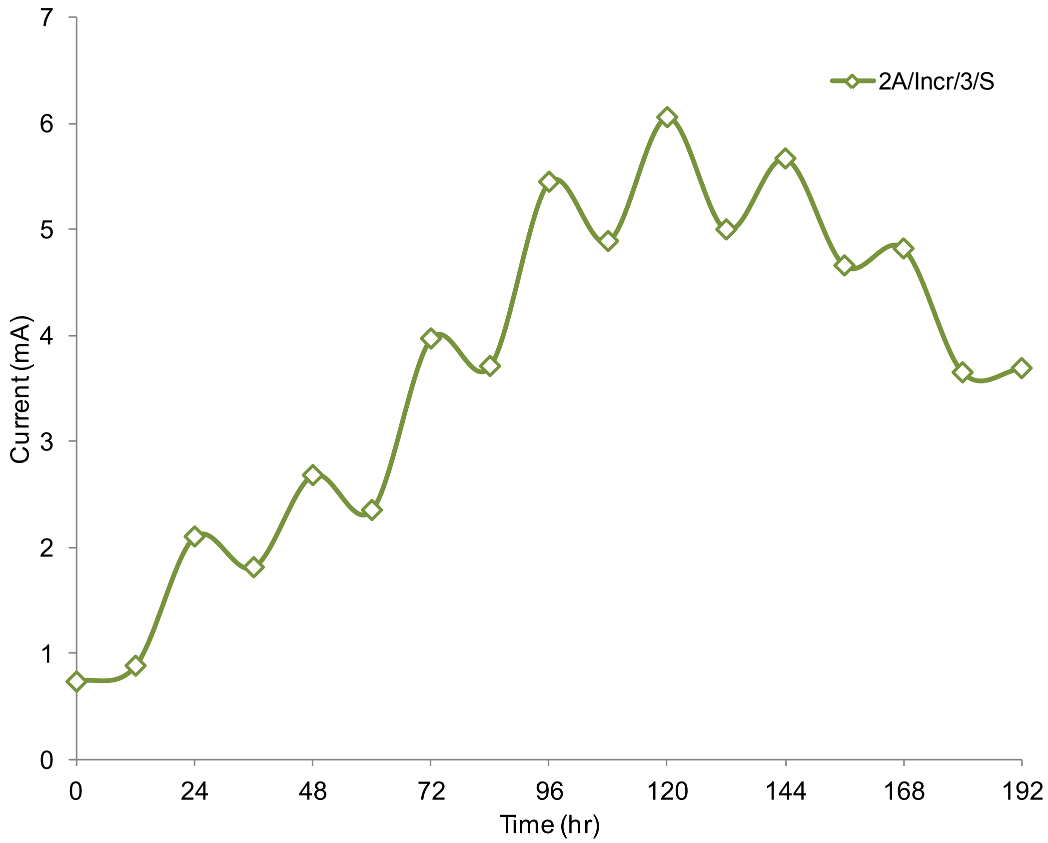
In the test with fixed voltage gradient of 80V/m, initial voltage loss near the cathode is 58% while voltage loss near the anode is 24%. This means that 18% of the applied voltage was transmitted through organic soil between the first and last voltage probes. At 72hr, voltage loss near the cathode decreases to 49% while voltage loss near the anode remains at 24%. As a result, voltage transmitted increases to 27%. This increment of transmitted voltage after 72hr of test is observed in peat as well. By 192hr, voltage loss at the cathode shows further reduction to 35% while voltage loss at the anode increases slightly to 29%. The voltage transmitted increases to 36%. The trend of decreasing voltage losses near the cathode is also observed in earlier tests on peat.

At the start of the test for incremental applied voltage, voltage losses near the cathode and anode is recorded as 40 and 52% respectively. This translates to 8% of the applied 10V/m voltage being transmitted through the organic soil. At 72hr, the voltage gradient was increased to 30V/m. Voltage loss recorded is 26% and 61% near the cathode and anode respectively. Voltage transmitted through the organic soil increases to 13%. By 192hr, voltage gradient was 80V/m, with voltage losses of 39% and 31% near the cathode and anode respectively. Voltage transmitted increases further to 39%. In the test with incremental voltage gradient, no significant trends is observed in the voltage losses near the anode and the cathode. The voltage losses show fluctuating magnitudes throughout the test.

Figure 4.23(b) shows the normalized measured voltage in peat during EO test with incremental voltage gradient. For the test with fixed voltage gradient of 80V/m, the instrumentation for voltage and current measurements was not included in the test setup. At the start of the test with incremental voltage gradient, initial applied voltage was 10V/m. Initial voltage loss is 43% and 43% at the first and last voltage probe respectively. This translates to 14% of the applied voltage transmitted through the peat. As the test progressed, voltage loss near the cathode reduces with time. Near the anode, voltage loss shows increment with time. At the end of the test, recorded voltage loss is 22% and 67% near the cathode and anode respectively. Voltage transmitted through peat has reduced to 11%. The increasing voltage loss near the anode is attributed to the drying of soil in the vicinity of the anode as well as reducing electrode-soil contact as a result of gas generation. This trend of decreasing voltage loss near the cathode and increasing voltage loss near the anode is also observed in the small scale EO tests in Section 4.2 earlier..



(a)



(b)

Figure 4.24: Variation of measured current with time during EO test on (a) organic soil and (b) peat with fixed 80V/m and incremental voltage gradient

Figure 4.24(a) shows the variation in measured current in the organic soil during EO tests with fixed voltage gradient of 80V/m and incremental voltage gradient. Upon application of DC, 22mA current was measured through the organic soil. Peak current of test with fixed voltage gradient is 32mA at 24hr. Following that, the measured current gradually reduces with time. At the end of the test, measured current through organic soil is 12mA.

In general, the trend in current of test with fixed 80V/m shows similarity to the trend of current in peat (Figure 4.12). The trend of higher measured current in the first few days of the test followed by gradual reduction with time observed in the test on peat is also seen in the test on organic soil. However, the range of measured current in organic soil is higher than that of peat. In peat, the measured current ranges from 5 to 13mA for test with voltage gradient of 80V/m. The higher magnitude of measured current in organic soil indicates the higher conductivity of organic soil.

In the test with incremental voltage gradient, initial measured current is low at 1.3mA. This is due to the low initial voltage gradient of 10V/m. Current was not measured from 12hr to 36hr due to faulty equipment. At 48hr, measured current in organic soil has increased to 6mA. With each increment of voltage gradient, the measured current also shows increase. This increasing trend continued until 144hr when voltage gradient was 60V/m. Measured current is 17mA which is the peak current in this test. After that, no further increase in current is observed even though voltage gradient was increased. A slight reduction in the measured current is observed from 144hr to 192hr.

Figure 4.24(b) shows the variation of measured current with time in peat during EO test with incremental voltage gradient. Initial measured current is 0.73mA due to low initial voltage gradient of 10V/m. With each increase in voltage gradient, the current through peat also shows increase. The measured current in peat peaks at 120hr with voltage gradient of 50V/m at 6mA. Following that, the current starts to decrease although voltage gradient was increased. Similar trend is observed in the incremental voltage gradient test on organic soil. Final measured current through peat at 192hr is 3.69mA.

The trend of measured current for fixed voltage gradient of 80V/m and incremental voltage gradient EO tests is reflected in the average flow per day of the respective test. Application of fixed voltage gradient resulted in higher current in the organic soil and peat at the early stages of the test. However, the current generated in the soil exhibited reduction as early as 48 hours into the test. This signifies the increase in overall resistance of the soil-electrical system. On the other hand, in the test with incremental voltage gradient, the current is low initially. With each increment in voltage gradient, the current shows increase as well. Peak current is reached at the later stage of the test. After the peak is achieved, no further increase in current is observed even though voltage gradient was increased. The overall range of measured current in the incremental voltage gradient test is lower than that of the fixed 80V/m test. With the overall lower range of current, settlement, moisture content reduction and strength gain of the organic soil and peat in the incremental voltage gradient test is expected to be lower than test with fixed voltage gradient of 80V/m.

In Section 4.3.2 earlier, the total volume of water collected for organic soil and peat showed similarity under the same testing conditions, in spite of the difference in initial moisture content between organic soil and peat. Hamed and Bhadra (1997) found that higher current resulted in higher EO flow. Hence the factor contributing to higher flow in organic soil might be the higher current in organic soil during EO. In the absence of measured current for test with fixed 80V/m on peat, it could only be postulated from the data of the small scale EO test of peat in Section 4.2.3 earlier. The current generated in peat is of a lower magnitude than that in organic soil. While the current in peat is not as high as organic soil, the EO flow in peat is comparable to that of the organic soil. This might be due to the high cation exchange capacity, CEC, (Huat *et al.,* 2014) and high moisture content of peat. High CEC and high moisture content might result in higher volume of water transported per unit of electrical charge transmitted (Mitchell and Soga, 2005).

4.3.4 Moisture content of organic soil and peat after EO tests

Soil samples for moisture content were obtained at three different locations in the test tank for the tests on organic soil and peat. Shelby tubes were used to collect soil samples at 7cm, 12.5cm and 18cm from the cathode. The soil sample extruded from the Shelby tube was divided into segments to obtain the final moisture content at different depths. Initial moisture content for organic soil was 302%, 306% and 287% for control test, test with fixed 80V/m and incremental voltage gradient respectively. Initial moisture content for peat was 663%, 654% and 628% for control test, test with fixed 80V/m and incremental voltage gradient respectively.

Table 4.2 shows the final moisture content of organic soil. Final moisture contents of the control test range from 254 to 301%, with lowest final moisture contents near the drainage well. For the test with fixed voltage gradient of 80V/m, final moisture contents range from 194 to 209%. In the test with incremental voltage gradient, final moisture contents range from 205 to 235%. Both tests with fixed and incremental voltage gradient show lower final moisture contents at the middle of the test bed and near the anode.

Table 4.2 also presents the reduction in moisture content of the organic soil. The reduction in moisture content is calculated as the percentage of change in moisture content over the initial moisture content. In the control test, reduction in moisture content is the lowest, ranging from 0.3 to 16%. For the test with fixed voltage gradient of 80V/m, reduction in moisture content ranges from 31 to 37%. This is the highest range of reduction in moisture content. The reduction of moisture content of the incremental voltage gradient test is lower, ranging from 18 to 28%.

Table 4.3 shows the final moisture content of peat. For the control test, final moisture contents range from 593 to 650%. In the test with fixed voltage gradient of 80V/m, final moisture contents range from 430 to 513%. Lowest final moisture contents are at 12.5cm and 18cm from the cathode. For the test with incremental voltage gradient, final moisture contents range from 383 to 557%. Lowest final moisture content is near the anode.

The reduction in moisture content of the tests on peat is also presented in Table 4.3. For the control test, reduction in moisture content is the lowest, similar to that in tests on organic soil. Reduction in moisture content ranges from 2 to 13%. In the test with fixed voltage gradient of 80V/m, reduction in moisture content ranges from 21 to 34%. The reduction in moisture content of the test with incremental voltage gradient shows higher variation with values ranging from 11 to 39%. Lower reduction is observed near the cathode while higher reduction is observed near the anode.

In the tests with incremental voltage gradient, the overall reduction in moisture content is lower than that of tests with fixed voltage gradient of 80V/m. This is reflected in the lower total volume of water collected in the tests with incremental voltage gradient. Higher reduction in moisture content is observed near the anode and middle of the test bed, while reduction in moisture content near the cathode is the lowest. The lower reduction of the tests with incremental voltage is attributed to lower voltage and current at the start of the test. The low voltage gradient and low current corresponds to lower EO flow. The lower EO flow results in lower volume of water transported to the cathode, observed as the lower volume of water recorded at the beginning of the test. At the later stages of the test, as the voltage gradient was increased, the EO flow increases. However, the EO flow at the later stage of the test is comparatively lower than the high EO flow at the start of the fixed 80V/m test. Hence, the total volume of water collected in the incremental voltage gradient test is lower than that of the fixed 80V/m test. This resulted in lower moisture content reduction of the tests with incremental voltage gradient.

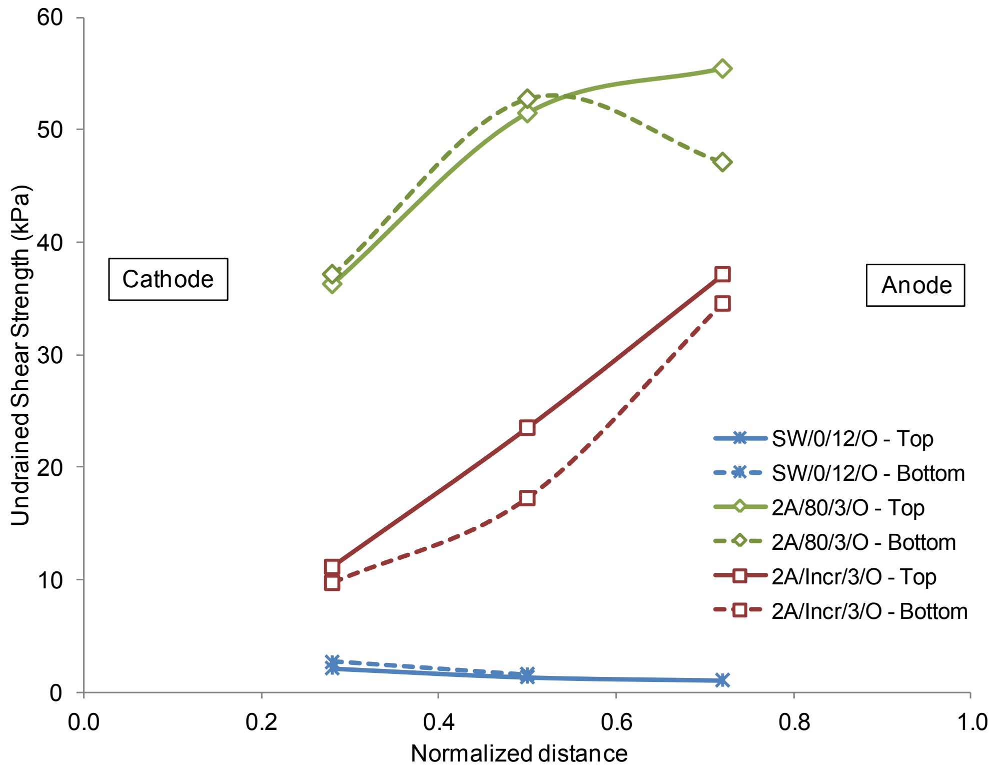
Table 4.2: Comparison of final moisture content post EO tests on organic soil with fixed 80V/m and incremental voltage

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
Control/12/O	302	268	290	299	11	4	1	0 - 3 cm
		277	299	301	8	1	0.3	3 - 6 cm
		266	303	305	12	-	-	6 - 9 cm
		254	300	297	16	0.6	1	9 - 12 cm
		-	292	-	-	3	-	12 – 14.5 cm
2A/80/3/O	306	209	199	200	31	35	34	0 – 2.5 cm
		198	194	192	35	37	37	2.5 - 5 cm
		204	195	196	34	36	36	5 – 7.5 cm
2A/Incr/3/O	287	234	216	209	18	25	27	0 – 2.5 cm
		214	216	205	25	25	28	2.5 - 5 cm
		235	208	208	18	27	27	5 – 7.5 cm
		223	-	206	22	-	28	7.5 – 10 cm

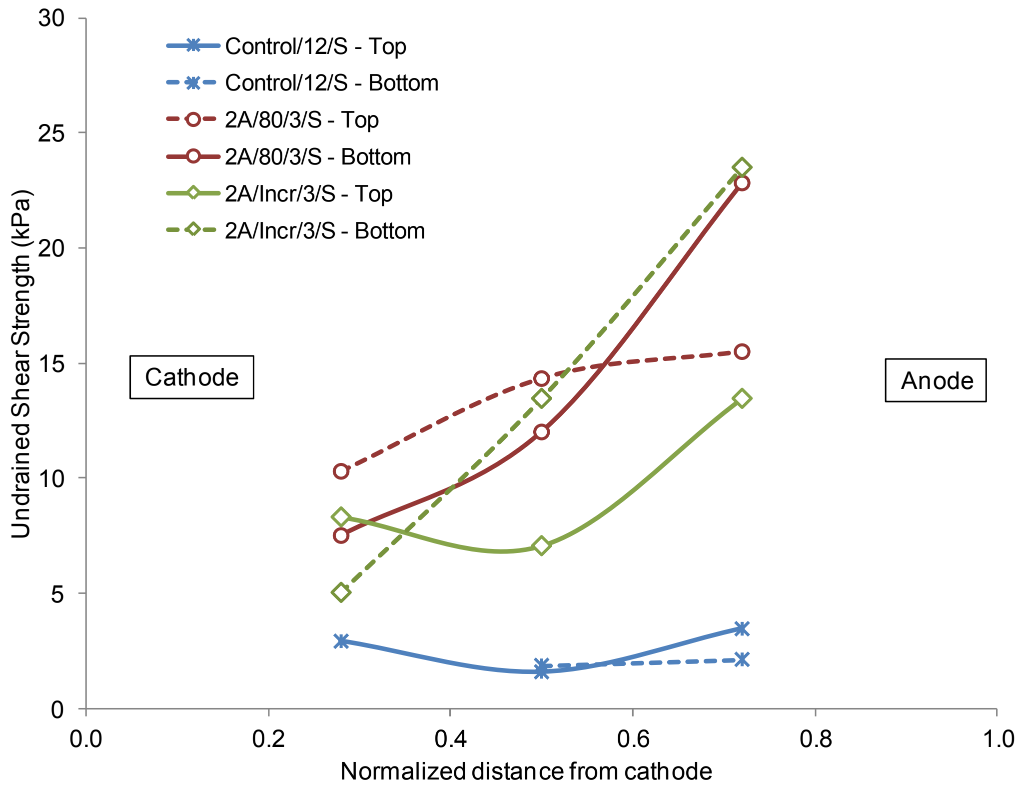
Table 4.3: Comparison of final moisture content post EO tests on peat with fixed 80V/m and incremental voltage gradient

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
Control/12/S	663	593	608	572	10	8	13	0 - 3 cm
		606	650	609	8	2	8	3 - 6 cm
		611	619	611	8	6	8	6 - 9 cm
		-	-	613	-	-	7	9 - 12 cm
2A/80/3/S	654	501	457	430	23	30	34	0 - 3 cm
		499	465	445	23	29	32	3 - 6 cm
		495	477	459	24	27	30	6 - 9 cm
		513	475	468	21	27	28	9 - 12 cm
2A/Incr/3/S	628	481	456	383	23	27	39	0 - 3 cm
		517	465	414	17	26	34	3 - 6 cm
		557	475	424	11	24	32	6 - 9 cm

4.3.5 Undrained shear strength of organic soil and peat after EO tests



(a)



(b)

Figure 4.25: Undrained shear strength post EO test on (a) organic soil and (b) peat with fixed 80V/m and incremental voltage

Figure 4.25(a) shows the final undrained shear strength of the organic soil after EO tests with fixed 80V/m and incremental voltage gradient. Laboratory vane shear tests were carried out at 0.28, 0.5 and 0.72 normalized distances from the cathode. Vane shear tests were conducted on the top and bottom of the organic soil. Initial shear strength of the organic soil was less than 2kPa for all three tests.

Vane shear test was not conducted at the bottom of the sample collected at 0.72 normalized distance from the cathode. This was because the vane could not be properly embedded in the soil collected in the Shelby tube. Final undrained shear strength of the control test ranges from 1.05 to 2.65kPa. No improvement is observed in the shear strength of the control test.

Test with fixed voltage gradient of 80V/m shows the highest strength gain. Final undrained shear strengths at the top and bottom of the organic soil bed show similarity except for the area near the anode. Final undrained shear strength ranges from 36 to 55kPa which is 3214 to 4911% of the initial shear strength. The area near the cathode underwent the lowest strength gain. The middle of the test bed and area near the anode show the highest improvement. The trend of the shear strength improvement is in agreement with the trend of moisture content reduction.

In the test with incremental voltage gradient, the final undrained shear strength is lowest near the cathode and highest near the anode. As observed in the test with fixed voltage gradient of 80V/m, the shear strength at the top and bottom of the test bed shows similarity. Final undrained shear strength ranges from 9.7 to 37kPa or 1054 to 4022% of the initial shear strength. The trend of the final undrained shear strength is reflected in the moisture content of the same test. Reduction in moisture content is lowest near the cathode and highest near the anode.

Figure 4.25(b) shows the final undrained shear strength of peat in the tests with fixed and incremental voltage gradient. Initial shear strength of the peat was less than 2kPa for all three tests. The control test shows the least improvement in shear strength. Vane shear test was not conducted on the sample collected from 0.28 normalized distance from the cathode as the vane could not be properly inserted into the peat due to sliding. Final undrained shear strength of the control test ranges from 1.9 to 2.9kPa.

Test with fixed voltage gradient of 80V/m on peat resulted in highest final undrained shear strength ranging from 7 to 23kPa. This is equivalent to an increase of 250 to 1050%. Highest undrained shear strength is observed near the anode while lowest undrained shear strength is near the cathode. The improvement in shear strength of the peat is in agreement with the moisture content reduction of the same test. However, the shear strength of the peat at the bottom near the anode did not show consistent strength gain with the reduction in moisture content of the peat.

In the test with incremental voltage gradient, the final undrained shear strength ranges from 5 to 23kPa. The final shear strengths show increment ranging from 150 to 1050% over the initial shear strength of peat. Larger variation in the final undrained shear strength of the test with incremental voltage gradient is observed. The trend of higher strength gain near the anode and lower strength gain near the cathode is still observed.

Although the volume of water collected in the tests on organic soil and peat show similarity, the final undrained shear strength of peat is comparatively lower than that of organic soil. This is attributed to the higher initial moisture content of peat. At the end of the test, the final moisture content of peat is at least twice that of organic soil. This resulted in significantly lower strength gain in peat.

4.4 Effect of constant current of 10mA and 20mA on EO of organic soil

EO tests were carried out with constant current on organic soil. This is done to study the effects of constant current on EO. Current density is one of the influencing factors on EO flow. The constant current for this test series was 10mA and 20mA. In order to monitor and maintain a constant current, an ammeter was included in the test setup. Details of the tests are found in Table 3.1. Initial moisture content for constant 10mA and 20mA was 308% and 311% respectively. Initial undrained shear strength was 1.19kPa for both tests. Figure 4.26 below shows the plan layout of EO tests on organic soil with constant current.

Figure 4.26: Plan view of test setup for EO tests on organic soil with constant current

4.4.1 Settlement profile of organic soil during EO tests

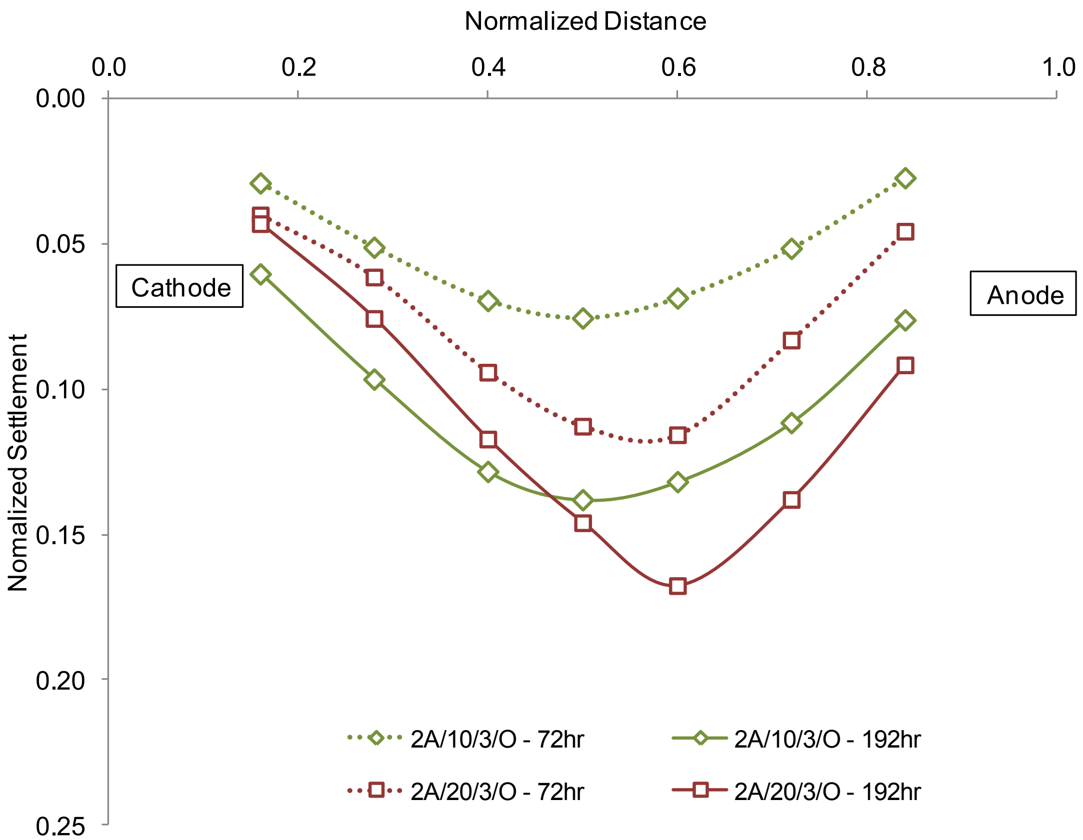
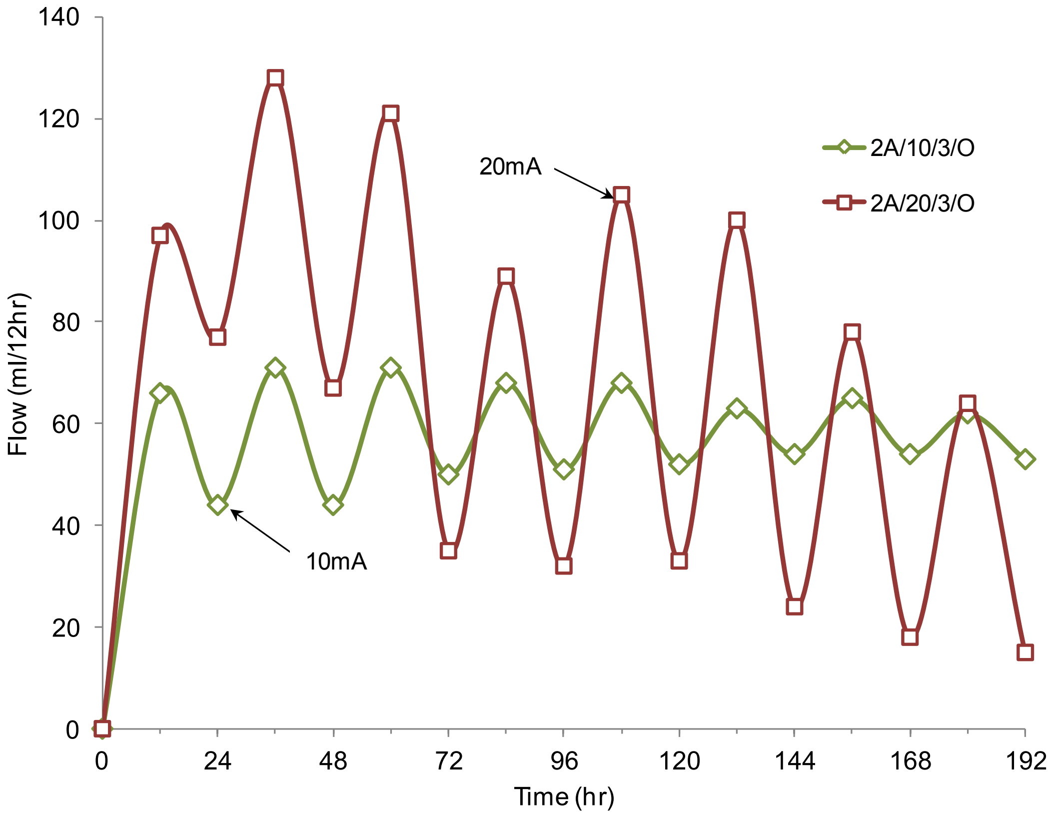


Figure 4.27: Normalized settlement profile with time of organic soil during EO tests with constant current of 10mA and 20mA

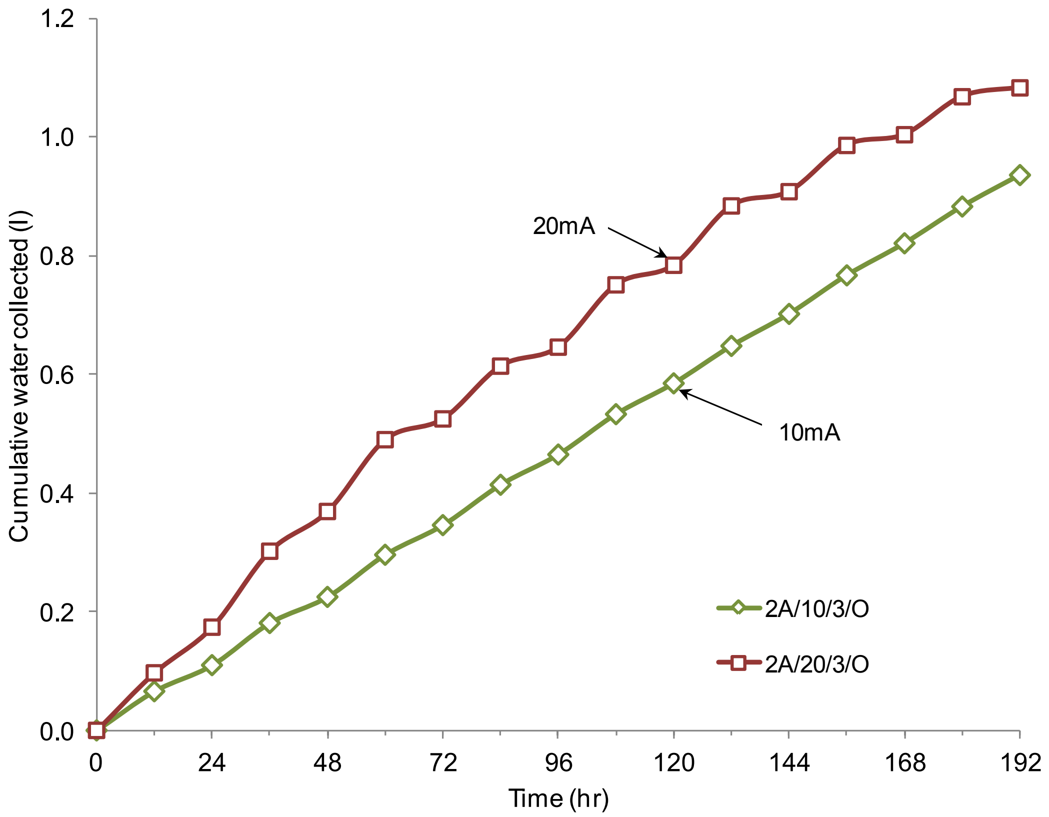
Figure 4.27 shows the normalized settlement profile of organic soil with time in the EO tests with constant current. Measured settlement values were normalized using the average initial height of 200mm. In the test with constant 10mA, at 72hr, maximum normalized settlement is 0.08 at 0.5 normalized distance. For the same time interval, the test with constant 20mA shows a higher rate of settlement. At 72hr, the maximum normalized settlement in the constant 20mA test is 0.12 at 0.6 normalized distance.

At the end of the test at 192hr, the maximum normalized settlement in the constant 10mA test is 0.14 at 0.5 normalized distance from cathode. From 72hr to 192hr, the maximum normalized settlement increases by 0.06. In the test with constant 20mA, at 192hr, maximum normalized settlement increases by 0.05 to 0.17 at 0.6 normalized distance from cathode. The overall settlement in the test with constant 20mA is higher than that of the test with constant 10mA. The difference between the maximum normalized settlement of constant 10mA and constant 20mA at 192hr is 0.03 or 3%.

4.4.2 Water collected during EO tests on organic soil



(a)



(b)

Figure 4.28: (a) Average flow and (b) cumulative volume of water collected during EO tests on organic soil with constant current of 10mA and 20mA

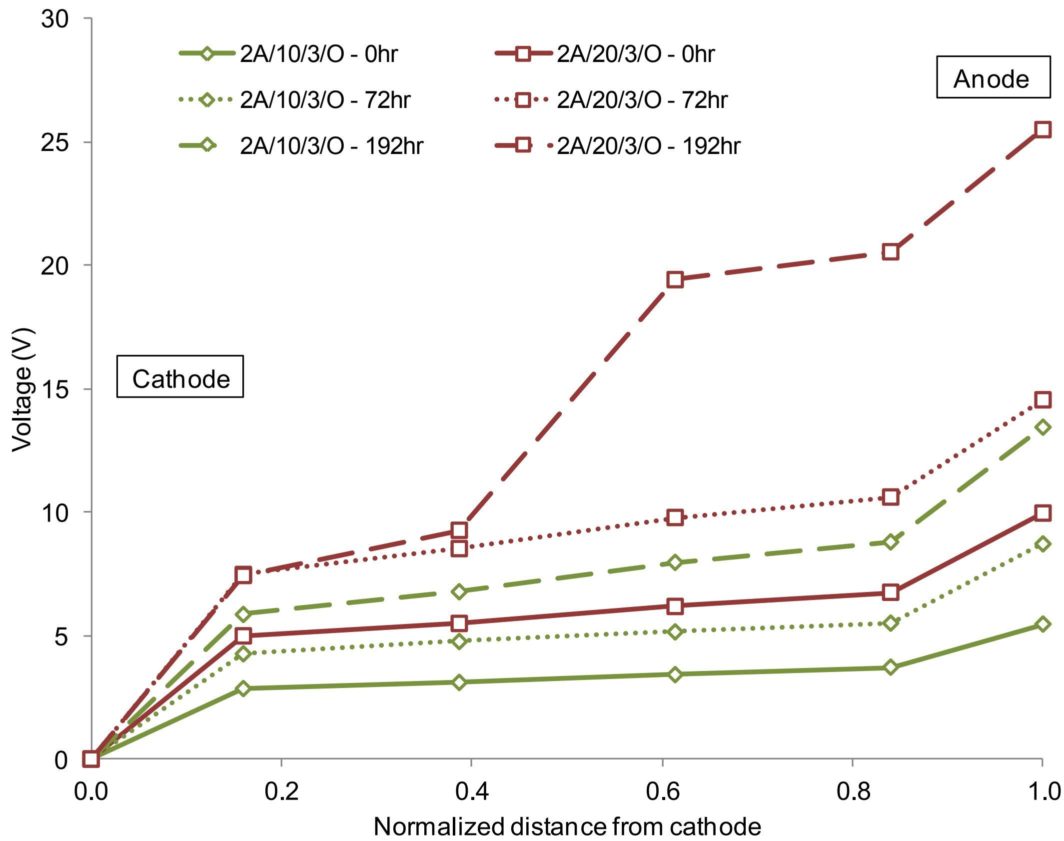
Figure 4.28(a) shows the average flow plotted over 12-hour intervals for the test with constant current in organic soil. In the test with constant 10mA, water collected from the drainage well before the start of the test was 34mℓ. In the first 12 hours, the flow is 66mℓ/12hr. In the following 12 hours, the flow reduces slightly to 44mℓl/12hr. The flow remains fairly constant throughout the test with a slight decreasing trend. Flow during the day ranges between 62 to 71mℓ/12hr. Flow during the night ranges from 44 to 54mℓ/12hr. The highest recorded flow of 71mℓ/12hr occurred at 36hr and 60hr.

For the test with constant 20mA, water collected before the application of DC was 29mℓ. Upon the start of the test, flow of water in the first 12 hours is 97mℓ/12hr. During the night, the flow reduces to 77mℓ/12hr. The flow increases to 128mℓ/hr at 36hr. The flow shows reduction with time from 60hr onward. At the end of the test, flow during the day has decreased to 64mℓ/12hr and flow during the night has reduced to 15mℓ/12hr.

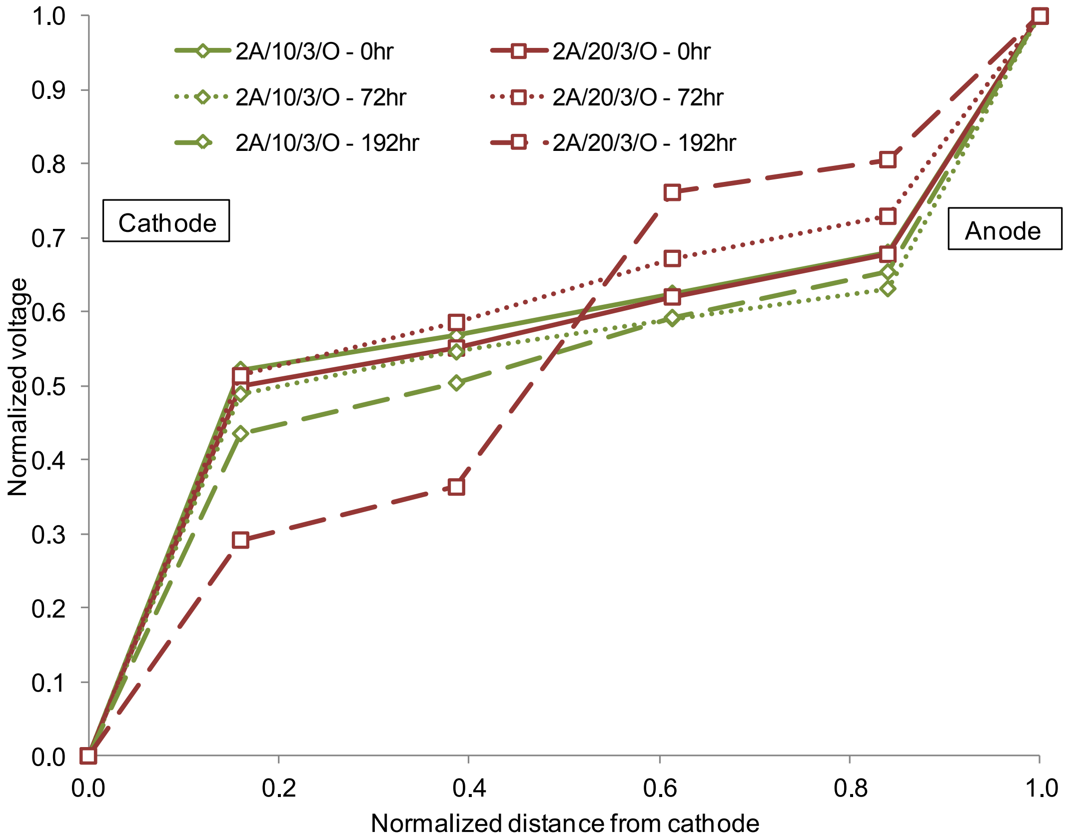
Figure 4.28(b) shows the cumulative volume of water collected during constant current EO tests on organic soil. In the test with constant 10mA, the total volume of water collected is 0.94ℓ. The cumulative flow shows an approximately linear trend throughout the test. In the test with constant 20mA, total volume of water collected is 1.08ℓ. Cumulative volume of water collected in the constant 20mA test is higher 15% higher than that of the test with constant 10mA. However, the flow in the constant 20mA test shows reduction while no reduction is observed in the lower current of 10mA. As observed in earlier EO tests, higher current transmitted through the soil corresponds to higher EO flow. Constant current of 20mA resulted in higher EO flow through organic soil than constant current of 10mA. Higher current of 20mA also resulted in earlier reduction of EO flow. Throughout the test duration, EO flow of the constant 10mA remained fairly constant without signs of reduction.

The cumulative flow of tests with constant current implies that EO flow is proportional to the current in the soil. Lower current induced lower EO flow during EO. However, no sign of reduction in EO flow is observed throughout the constant 10mA test. While higher current of 20mA resulted in higher EO flow, there is a gradual reduction of flow with time during the test.

4.4.3 Voltage and current in organic soil during EO tests



(a)



(b)

Figure 4.29: Variation of (a) measured and (b) normalized voltage in organic soil during EO tests with constant current of 10mA and 20mA

Figure 4.29(a) shows the variation of measured voltage in organic soil during tests with constant current of 10mA and 20mA. In order to maintain constant current, the voltage was constantly adjusted to achieve the required current. Hence the variation in voltage with time reflects the values of voltage applied throughout the test duration.

For the test with constant 10mA, initial required voltage was 5.5V, equivalent to 22V/m. Voltage measured in the organic soil ranges from 2.8 to 3.7V along the test bed. At 72hr, applied voltage of 8.7V or 34.8V/m was required. Voltage recorded in the organic soil is from 4.3 to 5.5V. At the end of the test, at 192hr, 13.4V or 53.6V/m was needed to maintain 10mA in the organic soil. Voltage measured in the organic soil ranges from 5.8 to 8.8V or 22 to 53.6V/m.

For the test with constant 20mA, initial required voltage was 10V, equivalent to 40V/m. The voltage required to maintain 20mA is nearly two times the voltage required for 10mA. Voltage measured in the organic soil ranges from 5.0 to 6.8V. At 72hr, applied voltage of 14.6V or 58.4V/m was required. Voltage recorded in the organic soil is from 7.5 to 10.6V. At the end of the test, at 192hr, 25.5V or 102V/m was needed to maintain 20mA through the organic soil. Voltage measured in the organic soil ranges from 7.4 to 20.6V. In order to generate higher current, higher applied voltage is required. In both tests, it is observed that applied voltage was constantly increased to maintain the required constant current. This indicates that the overall resistance of the system increases with time and results in reduction of current transmitted. To overcome the reduction in current, constant increment of applied voltage is necessary.

Figure 4.29(b) shows the variation of normalized voltage in organic soil during tests with constant current. The measured voltage is normalized using the applied voltage at the time of measurement. In the test with constant 10mA, initial voltage loss at 0.16 normalized distance from the cathode is 52%. Initial voltage loss at 0.84 normalized distance from the cathode is 32%. This corresponds to 16% of voltage being transmitted through the organic soil at the start of the test. At 72hr, voltage loss near the cathode reduces to 49% while voltage loss near the anode increases to 37%. The change in voltage losses reduces the voltage transmitted slightly to 14%. By 192hr, voltage loss near the cathode shows further reduction to 43%. Near the anode, voltage loss also shows reduction with 34%. The voltage transmitted through organic soil at the end of the test is 23%.

For the test with constant 20mA, initial voltage loss near the cathode and anode is 50% and 32% respectively. This translates to 18% of the applied voltage transmitted through the organic soil between the first and last voltage probe. At 72hr, voltage loss near the cathode increases slightly to 51% and voltage loss near the anode decreases to 27%. The voltage transmitted through organic soil at 72hr is 22%. By 192hr, voltage loss near the cathode and anode has reduced to 29% and 20% respectively.

4.4.4 Moisture content of organic soil after EO tests

Table 4.4 presents the final moisture content obtained from three different locations in the test for constant 10mA and 20mA. Final moisture content was obtained from the soil sample collected in Shelby tubes at 7cm, 12.5cm and 18cm from the cathode. The organic soil sample extruded from the Shelby tube was divided into segments to study the final moisture content at different depths.

In the test with constant 10mA, initial moisture content was 308%. Final moisture contents range from 231 to 253%, with higher final moisture content near the cathode and lower final moisture content near the anode. For the test with constant 20mA, initial moisture content was 311%. Final moisture contents range from 200 to 238%, also with higher final moisture content near the cathode and lower final moisture content near the anode. The overall lower final moisture content of the test with constant 20mA corresponds to the higher total volume of water collected of the same test.

Table 4.4 also shows the percentage of reduction in moisture content. The percentage of reduction in moisture content is calculated as the percentage of change in moisture content over the initial moisture content. For the test with constant 10mA, percentage of moisture content reduction ranges from 18 to 25%. With constant current of 20mA, percentage of moisture content reduction ranges from 24 to 35%. As seen in the final moisture content, higher reduction is observed in the test with constant 20mA. The test with constant current of 20mA has higher overall reduction in moisture content than that of test with constant 10mA. This is attributed to the higher current in the organic soil which increases rate of EO flow. Therefore, higher total volume of water is collected from the test with constant 20mA, leading to higher moisture content reduction.

Table 4.4: Comparison of final moisture content post EO tests on organic soil with constant 10mA and 20mA

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
2A/10/3/O	308	236	237	231	23	23	25	0 - 3 cm
		245	244	237	20	21	23	3 - 6 cm
		252	243	237	18	21	23	6 - 9 cm
		249	241	238	19	22	23	9 - 12 cm
		253	-	-	18	-	23	12 – 14 cm
2A/20/3/O	311	219	203	207	29	35	33	0 – 2 cm
		229	205	207	26	34	33	2 - 4 cm
		234	215	200	25	31	35	4 – 6 cm
		238	221	202	24	29	35	6 – 8.5 cm

4.4.5 Undrained shear strength of organic soil after EO tests

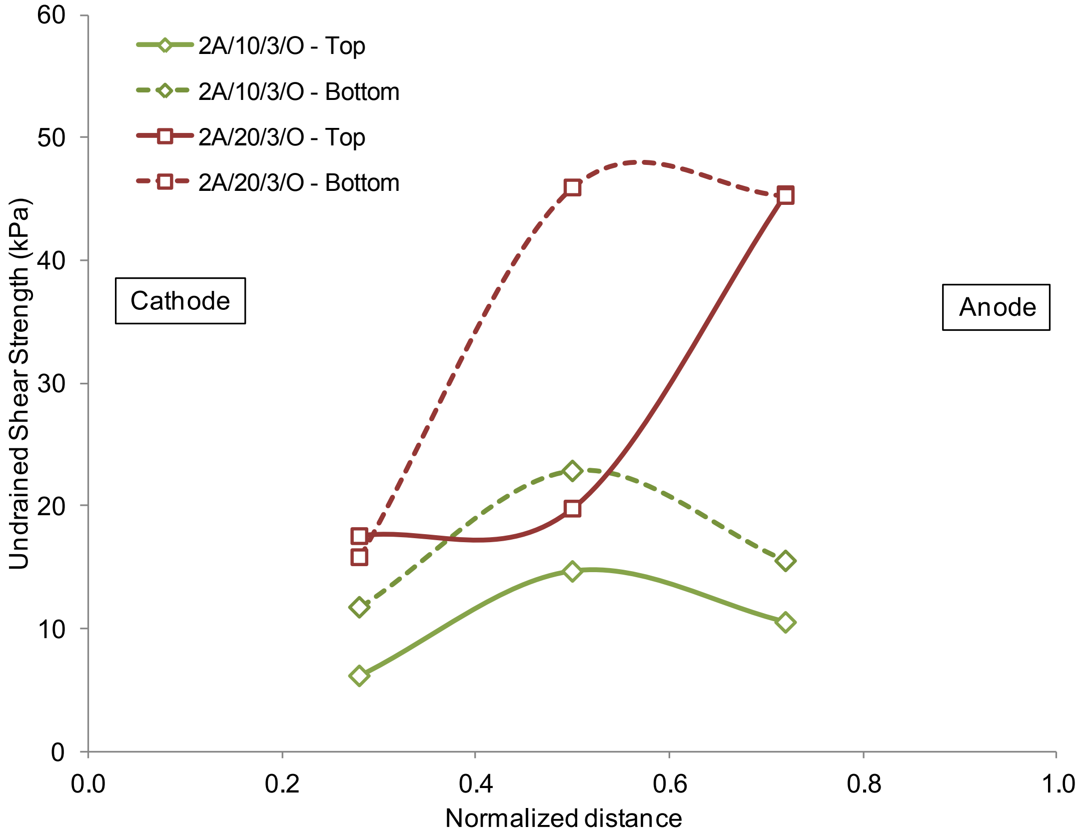


Figure 4.30: Undrained shear strength of organic soil post EO tests with constant current of 10mA and 20mA

Figure 4.30 shows the final undrained shear strength of organic soil in EO tests with constant current. Laboratory vane shear tests were carried out at 0.28, 0.5 and 0.72 normalized distances from the cathode. Vane shear tests were carried out at the top and bottom of the organic soil. Initial shear strengths were less than 2kPa in all three tests.

Final undrained shear strength for test with constant 10mA ranges from 6 to 23kPa. The middle of the test bed shows the highest strength gain. The final undrained shear strength of test with constant 10mA shows some inconsistency with the reduction in moisture content. For the test with constant 20mA, final undrained shear strength ranges from 16 to 46kPa. Highest improvement in shear strength is observed near the anode.

4.5 Chapter Summary

This chapter presented the observations and findings of the series of tests carried out to study the effect of applied voltage gradient on peat and organic soil. Tests with varied fixed voltage gradient were carried out in small scale and large scale laboratory tests. The effect of incremental applied voltage gradient was also evaluated in tests on peat and organic soil with small scale test setup. The influence of current density during EO consolidation is studied using fixed current tests on organic soil. Findings from the series of tests detailed in this chapter are listed below:

4.5.1 Fixed voltage gradient in small and large scale EO consolidation of peat

EO tests on peat were carried out in the small and large scale test setups. Voltage gradients were 80V/m, 100V/m and 120V/m. In the small scale test, test with voltage gradient of 100V/m shows larger settlement than test with voltage gradient of 80V/m. Voltage gradient of 120V/m did not result in larger settlement than that of test with voltage gradient of 100V/m. In the large scale test, settlement in the test with voltage gradient of 80V/m shows larger settlement compared to tests with voltage gradient of 100V/m and 120V/m. The overall average settlement for tests with voltage gradient of 100V/m and 120V/m did not show significant difference in spite of the different voltage gradient.

In the small scale EO tests, lowest volume of water was collected in the test with voltage gradient of 80V/m, in agreement with the lowest settlement of the test. Highest volume of water was collected in test with voltage gradient of 100V/m. The largest settlement of test with voltage gradient of 100V/m is not reflected in the volume of water collected. In the large scale EO tests, the highest volume of water collected is in the test with voltage gradient of 80V/m, reflecting the highest settlement. pH of the water collected in test with voltage gradient of 80V/m shows the lowest range. pH of water collected in the tests with voltage gradient of 100V/m and 120V/m showed higher ranges but without any significant different between the two tests.

Higher moisture content reduction was observed near the anode and the middle of the small scale test bed, while lower moisture content reduction is seen near the cathode. This indicates the direction of EO flow from anode to cathode. Reduction in moisture content is above 30% in all three tests. Maximum reduction in moisture content of 43%, 48% and 41% is recorded in the test with 80V/m, 100V/m and 120V/m respectively. Highest reduction in moisture content is in the 100V/m test.

Final pH of the peat after small scale EO tests did not exhibit large variations, with highest pH of 4.59 and lowest pH of 2.43. Initial pH of peat before EO test was pH 3.59. The low changes in pH values after EO test reflects the high buffer capacity of peat. At pH of lower than 3.5, EO flow still occurred in peat. No cessation of EO flow (at iso-electric point) or reversed EO flow (from cathode to anode) is observed during the test duration.

Highest improvement in shear strength is seen in the test with voltage gradient of 100V/m with a range from 33 to 54kPa translating to 3448 to5706%. The test with voltage gradient of 120V/m shows lower strength improvement although volume of water removed is high. This low strength improvement is attributed to cracks that developed in peat during the EO test.

In both the small and large scale EO tests, main voltage losses occur near the electrodes. Voltage loss near the anode increases with time due to the EO flow direction from anode to cathode and subsequent drying of the anode region. Voltage transmitted through peat reduces with time. Increase in voltage gradient increases the current through peat. Current in all EO tests show reduction with time. Formation of crack in the peat of the small scale test with voltage gradient of 120V/m resulted in reduced voltage and current transmitted through the peat.

The overall resistance of the EO tests show increase with time, in agreement with the reduction in moisture content of peat and subsequent reduction in conductivity. Main resistance of the system is observed in the vicinity of the electrodes. This could be due to increase in electrode-soil resistance resulting from gas generation. In the middle region of the test bed, the resistance of peat remained fairly constant throughout the test duration for the small scale tests. In the large scale tests, resistance of peat in the middle region shows gradual increment.

In the small scale EO tests, voltage gradient of 100V/m resulted in larger settlement, moisture content reduction and strength gain compared to the test with 80V/m. However, voltage gradient of 120V/m did not exhibit significant advantage over the test with 100V/m. Results of the test with different voltage gradients suggests a possible maximum voltage gradient resulting in largest settlement, highest volume of water collected and strength gain in the EO consolidation of peat. For the large scale tests, the possible maximum voltage gradient is voltage gradient of 80V/m.

4.5.2 Incremental voltage gradient in EO consolidation of organic soil and peat

For this series of tests, a control test without application of DC was included. Tests with application of DC are fixed voltage gradient of 80V/m and incremental voltage gradient of 10~80V/m, with average of 45V/m. The control tests show the lowest settlement. Application of DC expedited settlement of organic soil and peat. In tests with fixed voltage gradient of 80V/m, higher settlement rate was observed in the earlier stages of the tests. In tests with incremental voltage gradient, higher settlement rate was observed at the later stage of the tests when applied voltage was higher. In organic soil and peat, the overall settlement of test with fixed voltage gradient of 80% is higher than that of test with incremental voltage gradient. The difference in maximum of tests with fixed and incremental voltage gradient is 2% for organic soil and peat.

Total volume of water collected is lowest in the control tests. In the fixed voltage gradient 80V/m tests, highest volume of water is collected in organic soil and peat. Test with incremental voltage gradient shows 8% and 16% lower volume of water than the test with voltage gradient of 80V/m on organic soil and peat respectively. The tests with fixed voltage gradient show higher volume of water collected at the start of the test while tests with incremental voltage gradient show higher volume of water collected toward the end of the test.

The control tests exhibited no significant reduction in moisture content. In the tests with fixed voltage gradient of 80V/m, highest reduction in moisture content is observed. For the tests with incremental voltage gradient, overall lower reduction moisture content is observed. In both tests with fixed and incremental voltage gradient, reduction in moisture content is higher near the anode and lower near the cathode.

There is no improvement in shear strength of the control tests. Tests with fixed voltage gradient of 80V/m show the highest strength gain with final undrained shear strength ranging from 36 to 55kPa and 7 to 23kPa in organic soil and peat respectively. This translates to improvement of 3214 to 4911% and 250 to 1050% in organic soil and peat respectively. Lower strength gain is seen in the test with incremental voltage gradient. Final undrained shear strength ranges from 10 to 37kPa and 5 to 23kPa in organic soil and peat respectively. The increment in strength gain in tests with incremental voltage gradient is from 1054 to 4022% and 150 to1050% for organic soil and peat respectively.

The tests on organic soil also show voltage losses near the electrodes, similar to the observations of tests on peat. Measured current in organic soil shows higher magnitudes compared to the measured current in peat, reflecting the higher conductivity of organic soil. In the test with fixed 80V/m, measured current shows higher magnitude at the earlier stage of the test and reduction with time at the later stage. In the test with incremental voltage gradient, the measured current increases with each increment in voltage gradient. Peak current occurred at 144hr, with applied voltage of 60V/m. This is followed by gradual reduction with time.

Application of DC in organic soil and peat resulted in larger settlement, volume of water collected and strength gain compared to tests without application of DC In the tests with incremental voltage gradient, relatively lower settlement, volume of water collected and strength gain is observed compared to that of the tests with fixed voltage gradient of 80V/m.

4.5.3 Constant current in EO consolidation of organic soil

To study the effects of constant current on EO consolidation, two small scale tests were carried out in organic soil. Constant current applied was 10mA and 20mA. At the start of the test, the required voltage gradient to generate 10mA and 20mA in organic soil was 22V/m and 40V/m respectively. As the test progressed, current through organic soil reduces with time as the overall resistance increases. This resulted in constant increment of applied voltage to maintain the required constant currents. The applied voltage required for constant 20mA is approximately two times the voltage required for constant 10mA. At constant current of 20mA, maximum settlement is 3% higher than that of the test with constant current of 10mA.

EO flow in the test with 10mA constant current is fairly constant throughout the test duration with a slight reduction at the later stage of the test. The EO flow in test with constant 20mA shows more variation as higher EO flow is observed at the earlier stage of the test. Gradual reduction in flow is observed during the test duration. EO flow is proportional to the current. Higher current resulted in higher EO flow in organic soil. However, higher current also resulted in earlier reduction of EO flow during EO test.

Cumulative volume of water collected in the test with constant 10mA constant shows a linear trend throughout the test duration. Similar linear trend is seen in the test with 20mA constant current but with noticeable variation and reduction with time. With higher EO flow of the test with constant 20mA, the total volume of water collected is 15% higher than the test with constant 10mA.

Both tests with constant 10mA and 20mA show higher final moisture content near the cathode and lower final moisture content near the anode. The test with constant 20mA shows the highest overall reduction in moisture content with a maximum of 35%. The maximum reduction in moisture of the constant 10mA test is 25%.

Maximum final undrained shear strength in the constant 10mA and 20mA test is 23kPa and 46kPa respectively. The higher shear strength improvement of the constant 20mA test is in agreement with the higher total volume of water collected and higher reduction in moisture content.

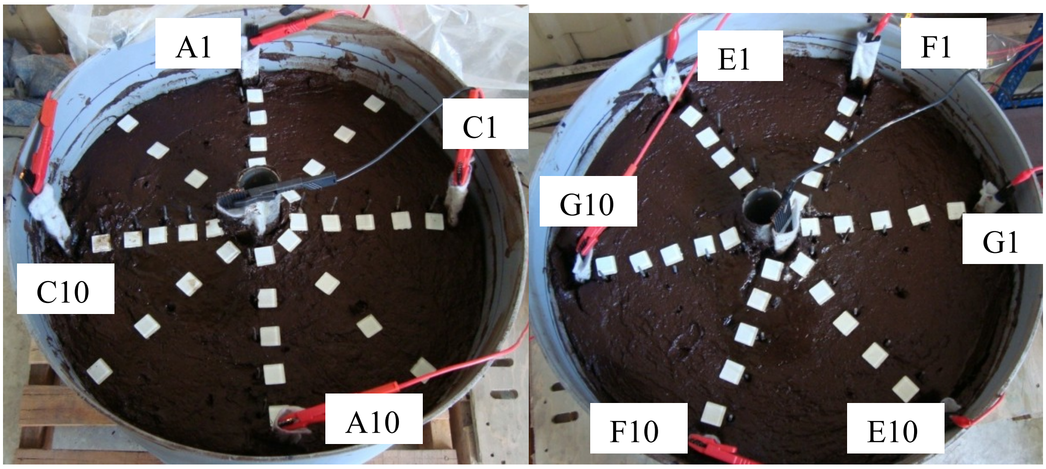
In the EO tests with constant current, in order to maintain the level of current in the soil, the applied voltage needs to be constantly increased. Uncontrolled increment of applied voltage to maintain constant current could lead to unduly high voltage gradients, which in turn could lead to unnecessary loss of energy and increase in running costs.

5 Effect of Radial Electrode Configuration on EO Consolidation of Peat

5.1 Introduction

This chapter presents the experiment findings and observations for the tests carried out to evaluate the effects of radial electrode configurations on EO consolidation. Two radial electrode configurations were chosen for this study, namely the square and hexagon electrode configurations. Figure 5.1(a) shows the square (R4) electrode configuration test setup. The R4 test setup is made up of a central cathode surrounded by four anodes. Figure 5.1(b) shows the hexagon (R6) electrode configuration. The R6 test setup consists of a central cathode surrounded by six anodes. A representative section taken between an anode and the central cathode of each electrode configuration is used in the analysis and discussion of the experimental results. The representative sections are A1-A5 and E1-E5 of the R4 and R6 electrode configuration test respectively.

A control test was conducted in the large scale test setup. Results of the control test showed that under self-weight conditions, there was minimal settlement. This was similar to the control tests carried out in the small scale tests. Hence results of the control tests were omitted for this chapter to avoid repetition.



(a) (b)

Figure 5.1: Plan view of test with (a) square, R4, and (b) hexagon, R6, electrode configurations

In each set of tests, the same voltage gradient was applied to the R4 and R6 radial electrode configurations. In the first set of tests, the applied voltage gradient was 80V/m or 0.8V/cm. Test duration was eight days. Initial moisture content was 516% and 351% for R4 and R6 respectively. Initial undrained shear strength was 1.58kPa and 4.19kPa for R4 and R6 respectively. For the second set of tests, applied voltage gradient was 100V/m or 1V/cm. Test duration was 16 days. Initial moisture content was 354% and 289% for R4 and R6 respectively. Initial undrained shear strength was 1.85kPa and 1.71kPa for R4 and R6 respectively. The third set of tests was carried out with voltage gradient of 120V/m or 1.2V/cm. Test duration was 12 days. Initial moisture content was 297% and 284% for R4 and R6 tests respectively. Initial undrained shear strength was 1.33kPa and 1.72kPa for R4 and R6 respectively. Further details of the tests are listed in Table 3.2.

5.2 Surface settlement of peat during R4 and R6 EO tests

5.2.1 Surface settlement profile of R4 and R6 EO tests with voltage gradient of 80V/m

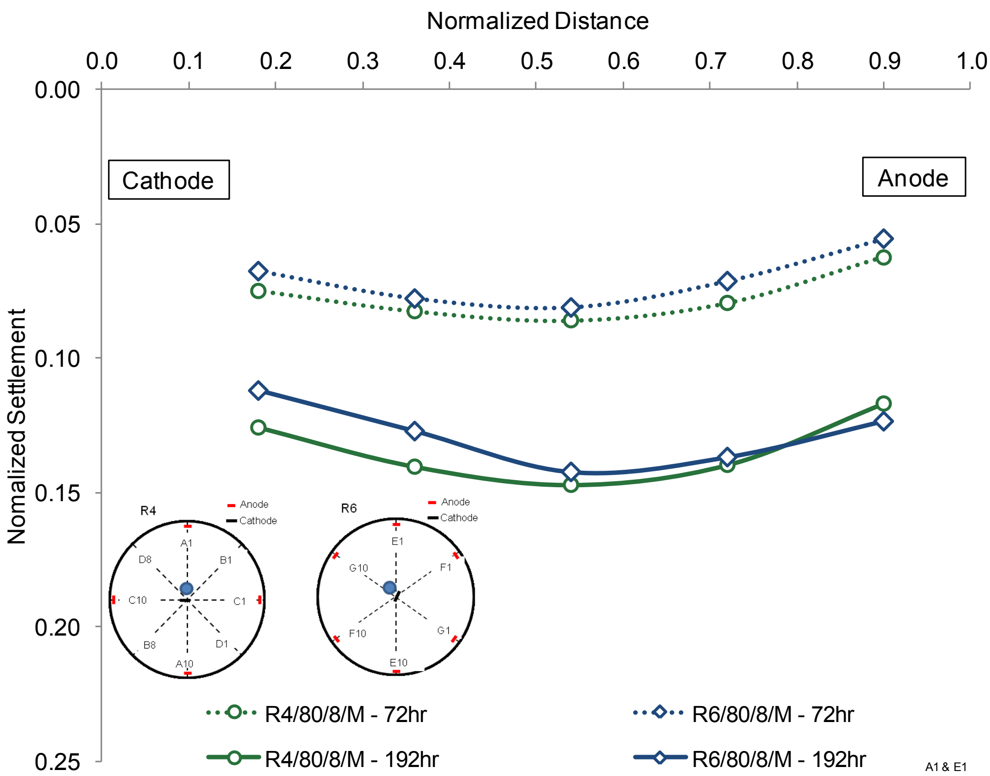


Figure 5.2: Normalized settlement profile along A1-A5 (R4) and E1-E5 (R6) during EO tests with 80V/m

Figure 5.2 shows the normalized settlement profile of peat at the representative sections of the R4 and R6 tests with time during EO tests with voltage gradient of 80V/m. Settlement data obtained during the test were normalized using the average initial height of peat, 500mm. The variations in normalized settlement with time along A6-A10 and Grids B, C & D for the R4 electrode configuration are shown in the Appendix from A 16 to A 19. Grids B & D of the R4 electrode configuration are located in the area without anodes. The variations in normalized settlement with time along E6-E10 and Grids F & G of the R6 electrode configuration are shown in the Appendix from A 20 to A 22.

At 72hr, the settlement profiles of the R4 and R6 are similar with marginally larger settlement observed in the R4 test. Along A1-A5, maximum normalized settlement is 0.080 at 0.54 normalized distance from the cathode. For the R6 test, maximum normalized settlement along E1-E5 is 0.081 at 0.54 normalized distance from the cathode. At 192hr, the settlement profiles of the R4 and R6 tests show more variation with larger settlements in the R4 test. Maximum normalized settlement of the R4 along A1-A5 is 0.147 while maximum normalized settlement of the R6 along E1-E5 is 0.127. This translates to a 16% higher maximum settlement in the R4 test.

5.2.2 Surface settlement profile of R4 and R6 EO tests with voltage gradient of 100V/m

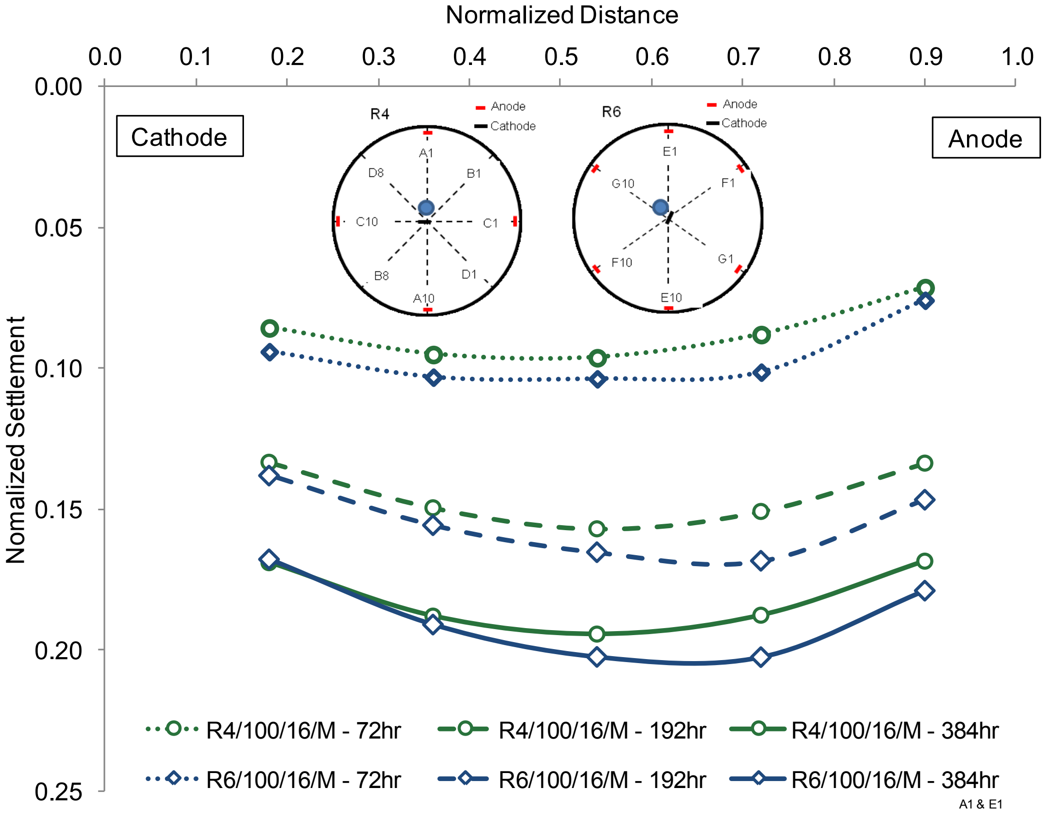


Figure 5.3: Normalized settlement profile along A1-A5 (R4) and E1-E5 (R6) during EO tests with 100V/m

Figure 5.3 shows the normalized settlement profile along A1-A5 of the R4 test and E1-E5 of the R6 test with voltage gradient of 100V/m. Settlement data obtained during the test were normalized using the average initial height of the peat, 470mm. The variation in normalized settlement with time along A6-A10 and Grids, B, C & D for the R4 electrode configuration is shown in the Appendix from A 36 to A 39. The variation in measured voltage with time along E6-E10 and Grids F & G for the R6 electrode configuration is shown in the Appendix from A 40 to A 42.

At 72hr, the R4 test show marginally lower settlement than the R6 test. Maximum normalized settlement at 72hr is 0.096 and 0.104 along A1-A5 and E1-E5 at 0.54 normalized distance from the cathode respectively. At 72hr, the maximum settlements for R4 and R6 tests with voltage gradient of 100V/m are larger than that of the tests with voltage gradient of 80V/m. At 192hr, maximum normalized settlements are 0.157 and 0.161 along A1-A5 and E1-E5 respectively.

The maximum normalized settlement of the R4 and R6 tests show larger magnitudes compared to that of tests with voltage gradient of 80V/m. The maximum normalized settlement at 192hr of test with voltage gradient of 100V/m is 7% and 27% higher than that of test with voltage gradient of 80V/m for R4 and R6 test respectively.

At the end of the test with voltage gradient of 100V/m, the maximum normalized settlement is 0.194 and 0.203 along A1-A5 and E1-E5 respectively. The R6 electrode configuration test shows marginally larger settlement along E1-E5 throughout the test duration. For the other anodes in the R4 test, the final maximum normalized settlement ranges from 0.180 to 0.192. For the other anodes in the R6 test, the final maximum normalized settlement ranges from 0.197 to 0.210. Marginally larger maximum normalized settlement is observed for the other anodes of the R6 test compared to that of the R4 test.

5.2.3 Surface settlement profile of R4 and R6 EO tests with voltage gradient of 120V/m

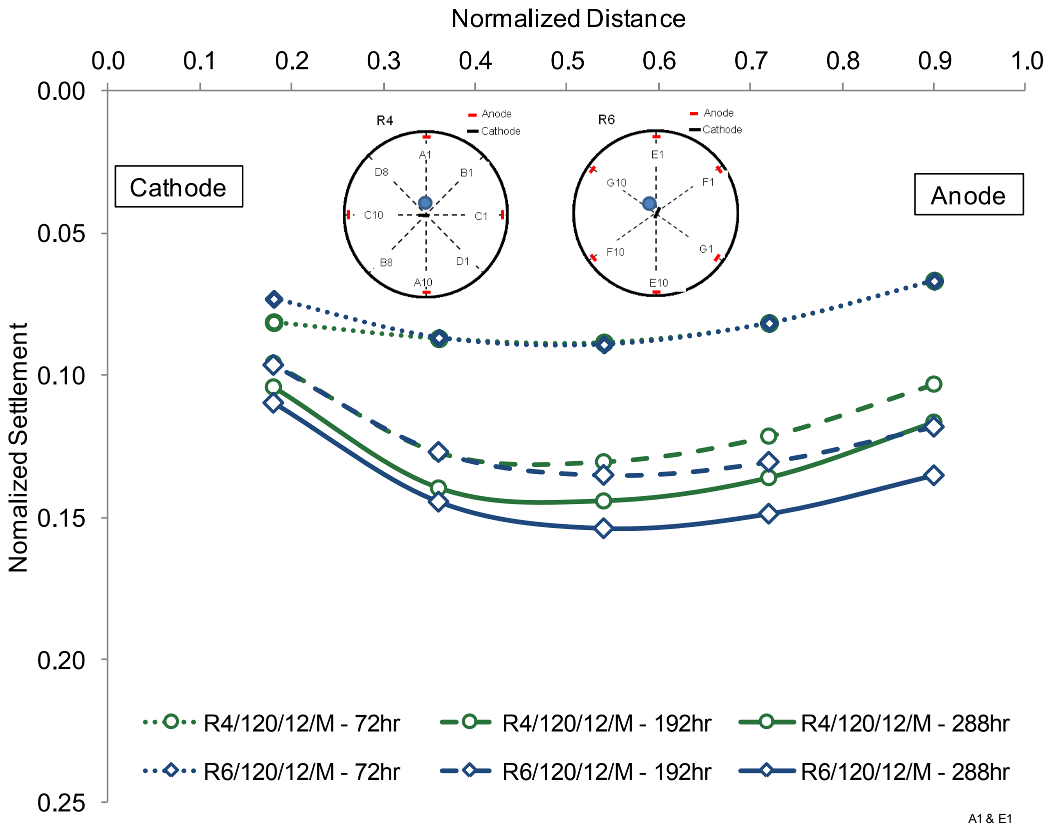


Figure 5.4: Normalized settlement profile along A1-A5 (R4) and E1-E5 (R6) during EO tests with 120V/m

Figure 5.4 shows the normalized settlement profile along A1-A5 of the R4 test and E1-E5 of the R6 test with time during EO tests with voltage gradient of 120V/m. The variation in normalized settlement with time along A6-A10 and Grids B, C & D for the R4 test is shown in the Appendix from A 56 to A 59. The variation in measured voltage with time along E6-E10 and Grids F & G for the R6 test is shown in the Appendix from A 60 to A 62.

At 72hr, maximum normalized settlement is 0.088 and 0.089 at 0.54 normalized distance from the cathode for R4 and R6 test respectively. No significant difference is observed in the settlement profile the R4 and R6 test. The maximum settlement at 72hr of R4 and R6 tests with voltage gradient of 120V/m is lower than that of tests with voltage gradient of 100V/m. Both the R4 and R6 tests with voltage gradient of 120V/m show marginally higher maximum settlement at 72hr than that of tests with voltage gradient of 80V/m.

At 192hr, settlement profiles of the R4 and R6 test show little variation near the cathode while larger variation is seen at the anode region. The maximum normalized settlement along A1-A5 to E1-E5 is 0.103 and 0.135 at 0.54 normalized distance from the cathode respectively. The settlement of the R4 and R6 tests with voltage gradient of 120V/m at 192hr is also lower than that of the tests with voltage gradient of 100V/m. The settlement of R4 and R6 tests with voltage gradient of 120V/m shows similar and at times lower magnitudes than that of the tests with voltage gradient of 80V/m. For both the R4 and R6 tests, higher voltage gradient of 120V/m did not result in the largest settlement at 192hr.

At the end of the test, at 288hr, the maximum normalized settlement along A1-A5 and E1-E5 is 0.144 and 0.154 respectively. The other anodes of the R4 test show larger maximum normalized settlement ranging from 0.147 to 0.163 at 0.54 normalized distance from the cathode. For the other anodes of the R6 test, the maximum normalized settlement ranges from 0.141 and 0.151, which is marginally lower than that of the R4 test.

5.2.4 Normalized average settlement of R4 and R6 EO tests

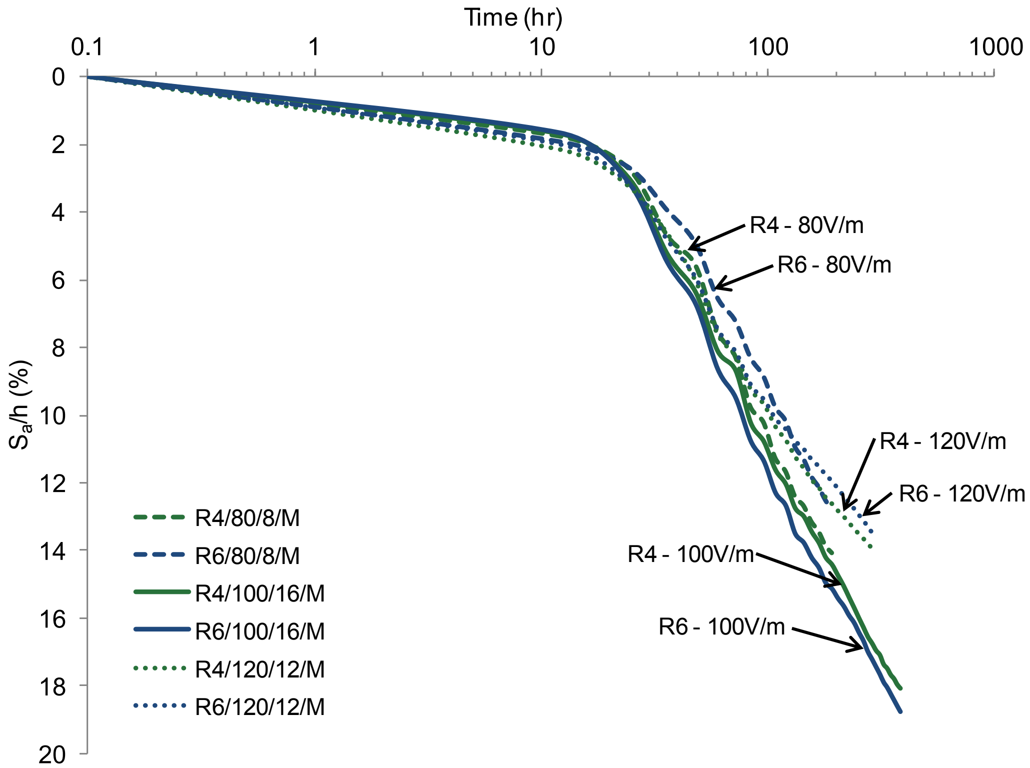


Figure 5.5: Normalized average settlement with time during R4 and R6 tests with voltage gradients of 80V/m, 100V/m and 120V/m

Figure 5.5 presents the normalized average settlement with time in square (R4) and hexagon (R6) electrode configuration during EO tests with voltage gradients of 80V/m, 100V/m and 120V/m. The normalized average settlement is obtained from data collected from all the settlement points of each test, normalized using initial height of peat.

With voltage gradient of 80V/m, the final normalized average settlement of the R4 and R6 test is 14.1% and 12.8% respectively. The difference between the average settlements is 1.3%. The hexagon (R6) electrode configuration was expected to yield higher settlement as seen in the mathematical modelling by Hu and Wu (2014). In the modelling, the voltage gradient was 20V/m. The area of soil treated was 8m^2 with a depth of 5m. The modelling results showed a 1.5% higher average surface settlement of the hexagon electrode configuration model compared to that of the square electrode configuration model. Although no direct comparison can be made due to the difference in test configurations, the mathematical modelling indicated that the hexagon electrode configuration resulted in higher settlement. However, from the tests with R4 and R6 electrode configuration at voltage gradient of 80V/m, the normalized average settlement of the R4 test shows higher settlement than the R6 test.

At 192hr of the R4 and R6 tests with voltage gradient of 100V/m, the normalized average settlement is 14.4% and 15.1% respectively. The average settlement of the R6 test is marginally higher than that of the R4 test. The average settlement of the R4 test with voltage gradient of 100V/m is marginally higher than that of the R4 test with voltage gradient of 80V/m at 192hr. For the R6 test, the average settlement at 192hr with voltage gradient of 100V/m is 2.3% higher than that of the test with voltage gradient of 80V/m. The final average settlement of the R4 and R6 test with voltage gradient of 100V/m is 18.1% and 18.8% respectively. At 384hr, the R6 test shows 0.7% higher average settlement than the R4 test.

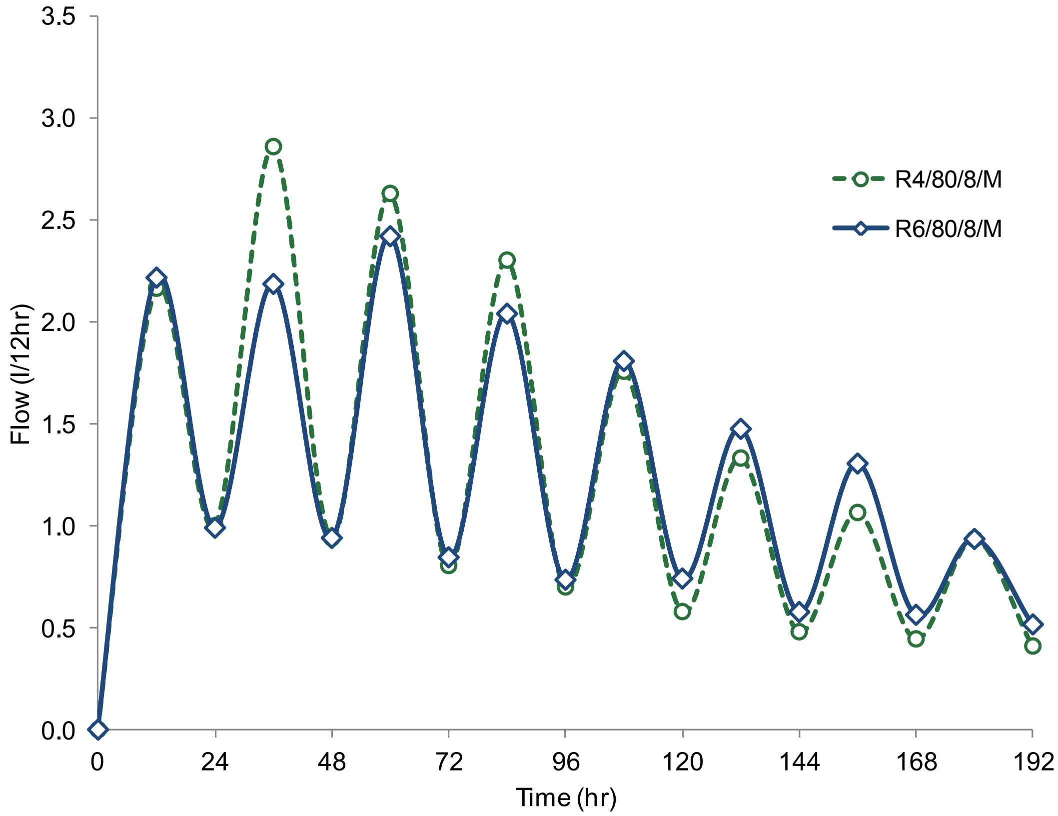
For the R4 and R6 tests with voltage gradient of 120V/m, the normalized average settlement at 192hr is 12.7% and 12.0% respectively. At 192hr, the average settlement of the R4 test is marginally higher than that of the R6 test. With voltage gradient of 120V/m, the average settlement at 192hr is lower than that of the tests with voltage gradients of 80V/m and 100V/m. At the end of the test, at 288hr, the final average settlement of the R4 and R6 test with voltage gradient of 120V/m is 13.9% and 13.5% respectively. This is again lower than the average settlement of 18.4% and 17.8% at 288hr in the R4 and R6 test with voltage gradient of 100V/m respectively. For the tests with voltage gradient of 120V/m, the R4 test shows a marginally higher average settlement of 0.4% than the R6 test.

In the R4 test, the normalized average settlement at 192hr is 14.1%, 14.4% and 12.6% for voltage gradient of 80V/m, 100V/m and 120V/m respectively. For the R6 test, the normalized average settlement at 192hr is 12.8%, 15.1% and 12.0% for voltage gradient of 80V/m, 100V/m and 120V/m respectively. Both the R4 and R6 electrode configuration tests show highest settlement at 192hr with voltage gradient of 100V/m. This is observed earlier in the small scale EO test with voltage gradient of 100V/m (Section 4.2.1), where the highest settlement was achieved. This indicates the possibility of an optimum voltage gradient where the resulting settlement is highest. Application of higher voltage gradient than the possible optimum voltage gradient would not result in further increase in settlement.

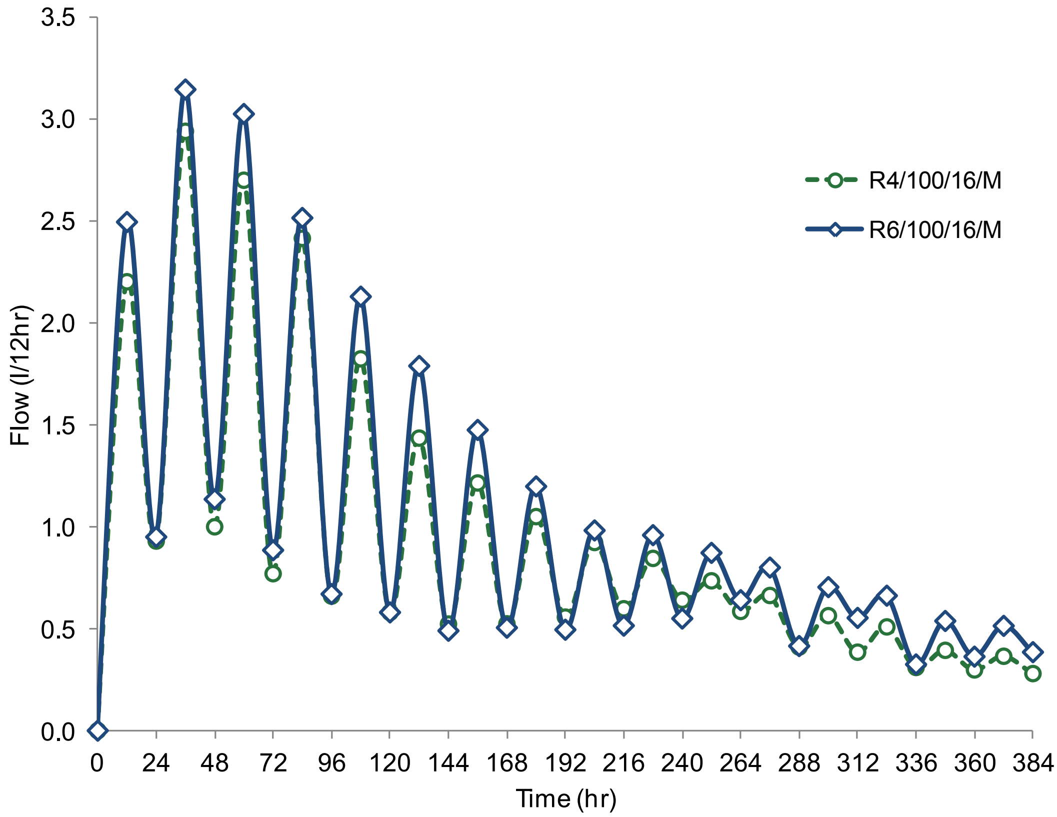
5.3 Water collected during R4 and R6 EO tests on peat

During the EO tests, water in the drainage well was collected at 3hr intervals for 12 hours during the day. Following that, for 12 hours during the night, water collected in the drainage well was left overnight.

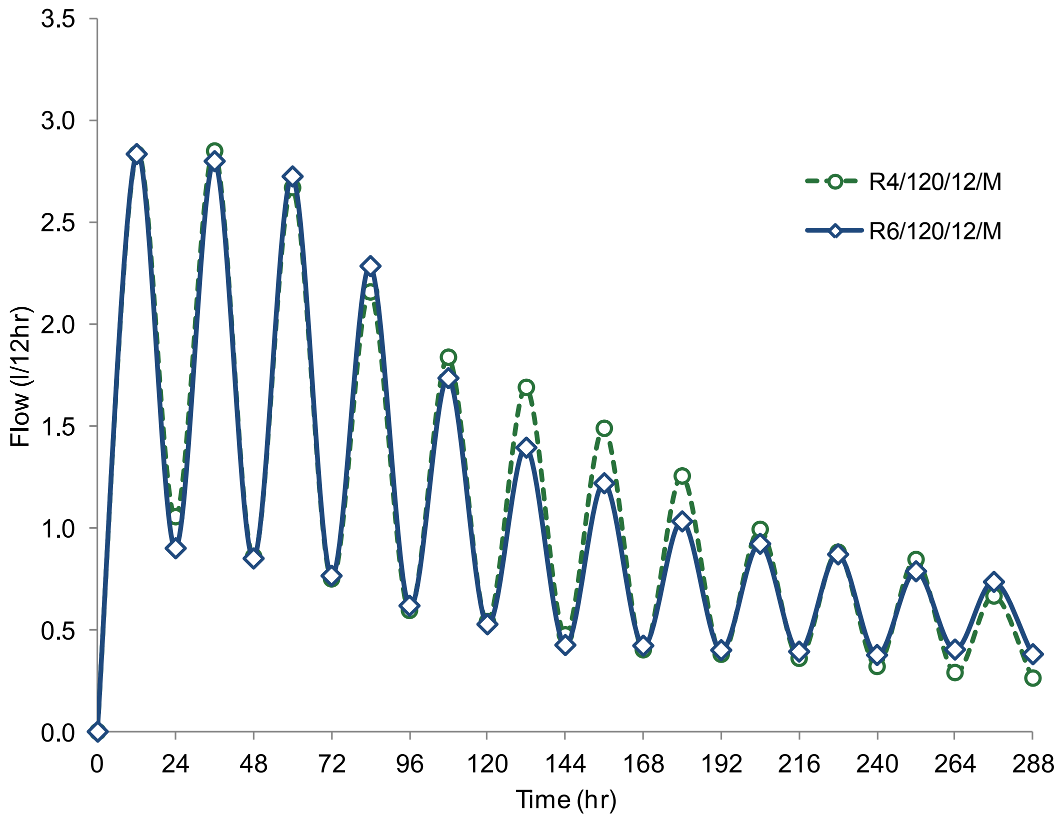
5.3.1 EO flow during R4 and R6 EO tests on peat



(a)



(b)



(c)

Figure 5.6: EO flow during EO tests with R4 and R6 electrode configuration at voltage gradient of (a) 80V/m, (b) 100V/m and (c) 120V/m

Figure 5.6(a) shows the average EO flow during R4 and R6 electrode configuration tests with voltage gradient of 80V/m. The initial flow at the start of the test was 2.13ℓ/12hr and 2.22ℓ/12hr for R4 and R6 test respectively. In the R4 test, the highest average flow occurred at 36hr with 2.86ℓ/12hr. Peak average flow in the R6 test occurred at 60hr with 2.42ℓ/12hr. The higher peak flow in the R4 test might be due to higher initial moisture content, resulting in more free water available during EO compared to the R6 test. After the peak flow in each test, gradual reduction with time in flow is observed. The test with R4 electrode configuration initially shows higher average flow. However the average flow in the R4 test exhibited larger decline from 120hr onward. For the same period of time, the average flow in the R6 test shows lower reduction, resulting in higher average flow at the later stage of the test compared to that of the R4 test.

Figure 5.6(b) shows the average EO flow during R4 and R6 electrode configuration tests with voltage gradient of 100V/m. Initial flow at the start of the test is 2.20ℓ/12hr and 2.49ℓ/12hr for R4 and R6 respectively. The peak flow for both tests occurred at 36hr with 2.94ℓ/12hr and 3.14ℓ/12hr for R4 and R6 respectively. At voltage gradient of 100V/m, the R6 test shows higher EO flow throughout the test duration. Reduction with time in the EO flow is also observed after peak flow, with higher reduction in the R4 test. EO flow of R4 and R6 tests with voltage gradient of 100V/m is higher than that of R4 and R6 tests with voltage gradient of 80V/m.

Figure 5.6(c) presents the average EO flow during R4 and R6 electrode configuration tests with voltage gradient of 120V/m. Initial flow is 2.83ℓ/12hr and 2.83ℓ/12hr for R4 and R6 test respectively. Unlike the tests with voltage gradient of 80V/m and 100V/m, the peak flow of the tests with voltage gradient of 120V/m occurred at the start of the test. For the tests with voltage gradient of 80V/m and 100V/m, the peak flow occurred after 24hr. However, gradual reduction with time is also observed in the EO flow at voltage gradient of 120V/m. The trend of peak flow following by a decreasing trend was reported by Asadi *et al.* (2010) and Eykholt and Daniel (1994). In their studies, peak flow occurred after two days of testing, observed only in the tests with voltage gradients of 80V/m and 100V/m.

Comparison of the R4 electrode configuration test at voltage gradients of 80V/m, 100V/m and 120V/m shows that the highest EO flow occurred at voltage gradient of 100V/m. Voltage gradient of 120V/m did not result in the highest flow with the R4 electrode configuration test. For the R6 electrode configuration test, with voltage gradients of 80V/m, 100V/m and 120V/m, test with voltage gradient of 100V/m also shows the highest flow. As observed in the R4 electrode configuration tests, voltage gradient of 120V/m also did not result in the highest flow with the R6 electrode configuration test.

5.3.2 Cumulative water collected during R4 and R6 EO tests on peat

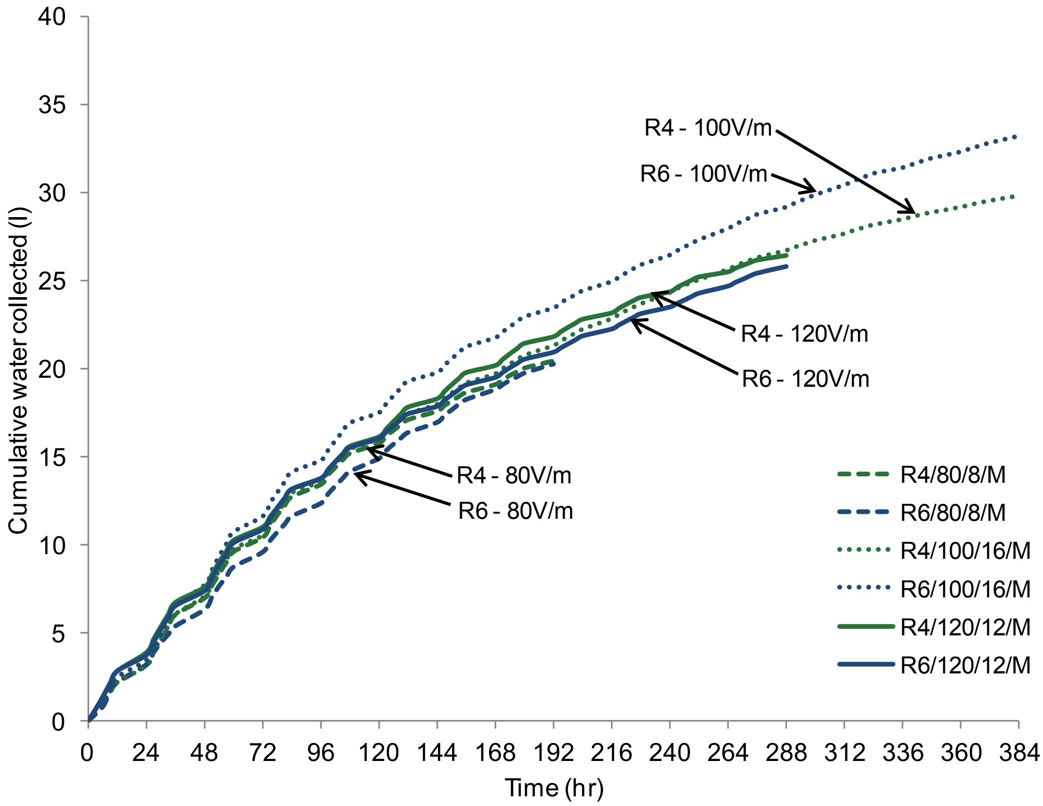


Figure 5.7: Cumulative water collected in EO tests with R4 and R6 electrode configuration at voltage gradient of 80V/m, 100V/m and 120V/m

Figure 5.7 shows the cumulative water collected during EO tests with R4 and R6 electrode configuration at voltage gradients of 80V/m, 100V/m and 120V/m. In the tests with voltage gradient of 80V/m, water collected in the drainage well before the start of test was 0.39ℓ and 0.38ℓ for R4 and R6 respectively. In the R4 test, volume of water collected at 24hr is 3.15ℓ. By 72hr, 10.4ℓ is collected, which amounts to slightly more than half of the total volume collected. Higher flow was observed at the earlier stage of the test. Total volume of water collected in the R4 test is 20.4ℓ.

For the R6 test, 3.21ℓ of water is collected in the first 24 hours. The volume of water collected at 72hr for R6 test is 9.60ℓ, which is slightly lower than half of the total volume of 20.29ℓ. This is reflected in the relatively lower flow at the earlier stages of the R6 test compared to that of the R4 test. At the later stage of the R6 test, the EO flow showed lower reduction compared to the R4 test. This resulted in similar total volume of water collected in both tests. The difference in total volume of water collected of the R4 and R6 test is only 0.11ℓ or 0.5%. The total volume of water collected in the R4 test is inconsistent with the higher average settlement of the same test.

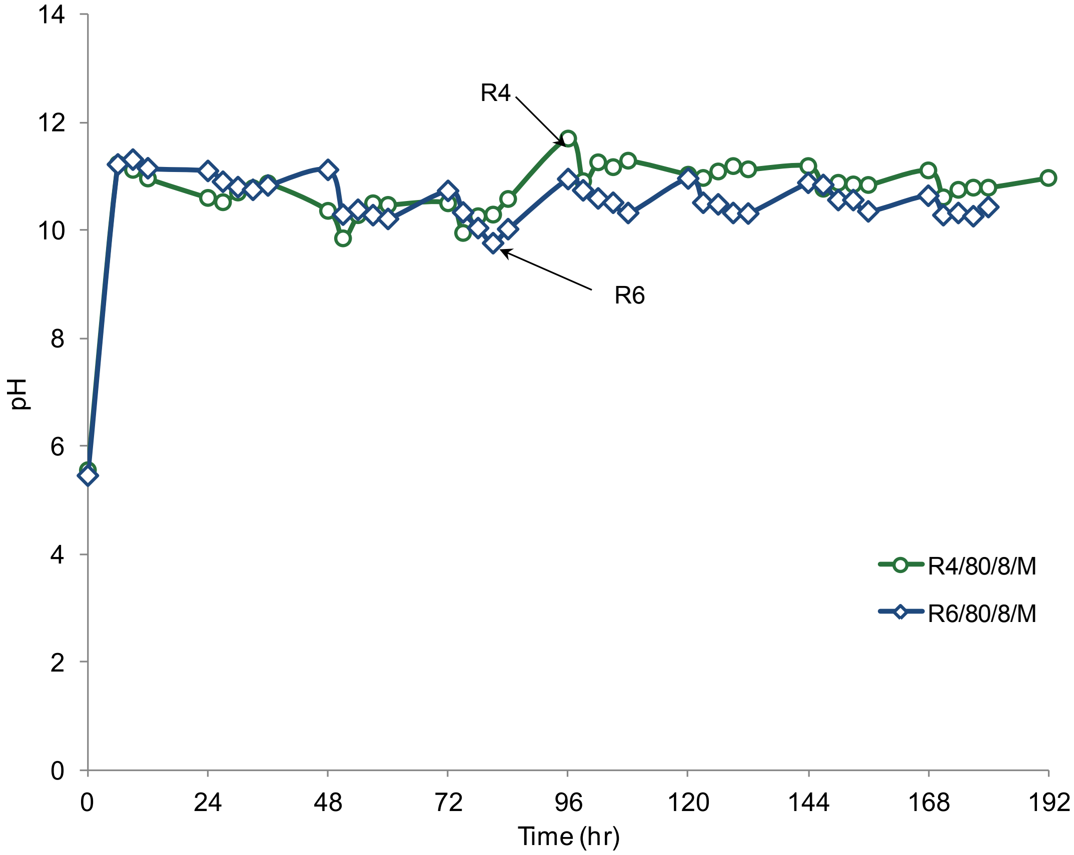
In the R4 and R6 EO tests at voltage gradient of 100V/m, water collected before the start of the test was 0.28ℓ and 0.26ℓ respectively. At 24hr, volume of water collected is 3.13ℓ and 3.44ℓ for R4 and R6 respectively. The volume of water collected in the R6 test is 0.23ℓ higher than that of the R4 test. As the test progressed, the R6 test consistently shows higher volume of water collected. This is reflected in the higher EO flow and settlement of the R6 test compared to that of the R4 test. At 192hr, volume of water collected for the R4 and R6 test is 21.3ℓ and 23.5ℓ respectively. The volume of water at 192hr for both R4 and R6 tests with voltage gradient of 100V/m is higher than that with voltage gradient of 80V/m. For the EO tests with voltage gradient of 100V/m, total volume of water collected at 384hr is 29.83ℓ and 33.26ℓ for R4 and R6 respectively. The difference in total volume of water collected between the R4 and R6 test is 3.43ℓ or 11%.

For the R4 and R6 tests with voltage gradient of 120V/m, water collected before the start of the test was 0.19ℓ and 0.16ℓ respectively. At 24hr, volume of water collected is 3.89ℓ and 3.73ℓ for R4 and R6 respectively. From 0hr to 120hr, no significant difference is observed in the volume of water collected from the R4 and R6 tests. From 120hr onward, the R4 test starts to show higher volume of water collected. At 192hr, volume of water collected is 21.84ℓ and 20.93ℓ for R4 and R6 test respectively. The volume of water collected at 192hr in the test with voltage gradient of 120V/m is marginally higher than that with voltage gradient of 100V/m. The volume of water collected at 192hr in the R6 test with voltage gradient of 120V/m is lower than that with voltage gradient of 100V/m. At the same time, the volume of water at 192hr in the R4 and R6 test with voltage gradient of 120V/m is marginally higher than that with voltage gradient of 80V/m. At 288hr, total volume of water collected is 26.46ℓ and 25.80ℓ for R4 and R6 respectively. The total volume of water collected in the R4 test is 0.66ℓ or 2.5% higher than that of the R6 test. This is reflected in the higher normalized average settlement of the R4 test with voltage gradient of 120V/m.

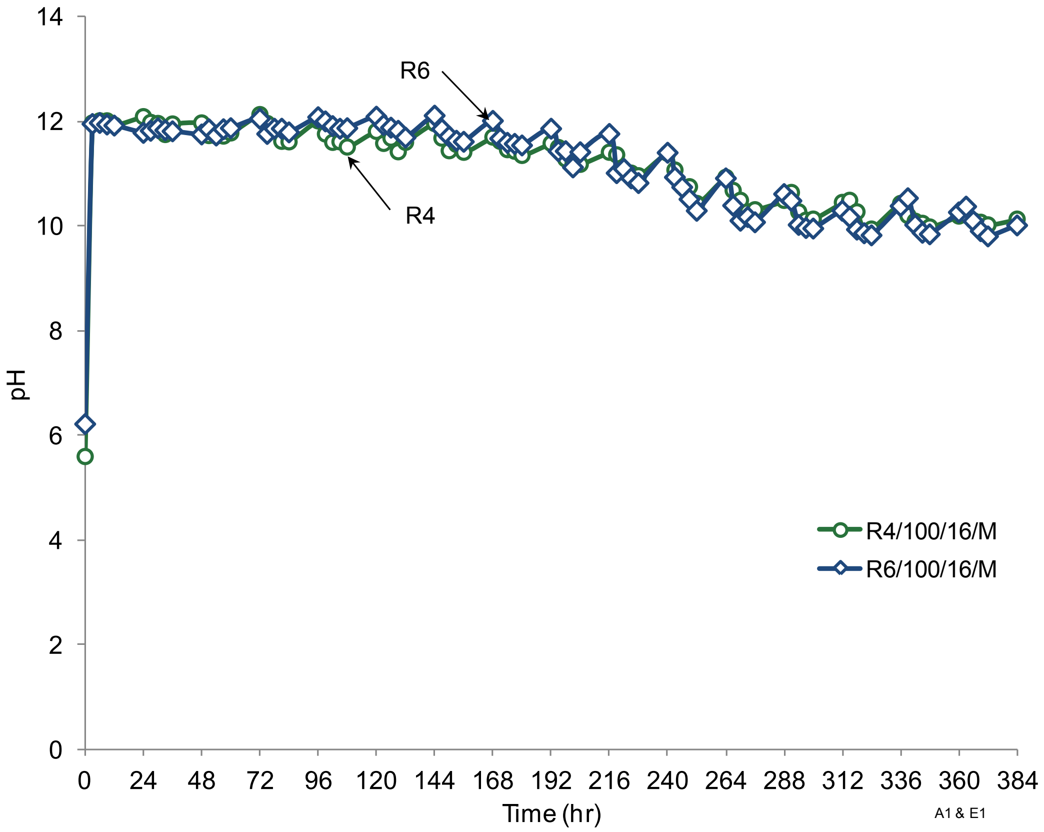
With the R4 electrode configuration, volume of water collected at 192hr was 20.41ℓ, 21.32ℓ and 21.84ℓ for voltage gradient of 80V/m, 100V/m and 120V/m respectively. Higher applied voltage gradient only induced marginally higher total volume of water collected. Highest total volume of water collected is observed in the R4 test with voltage gradient of 120V/m. The total volume of water collected in the R4 test at different voltage gradients is inconsistent with the settlement of the same tests. At 192hr, largest settlement is observed in the R4 test with voltage gradient of 100V/m.

In the R6 electrode configuration tests, volume of water collected at 192hr was 20.29ℓ, 23.48ℓ and 20.93ℓ for voltage gradient of 80V/m, 100V/m and 120V/m respectively. The highest volume of water is collected in the R6 test with voltage gradient of 100V/m. This is in agreement with the largest settlement of the same test. Application of higher voltage gradient of 120V/m did not induce higher EO flow in the R6 test.

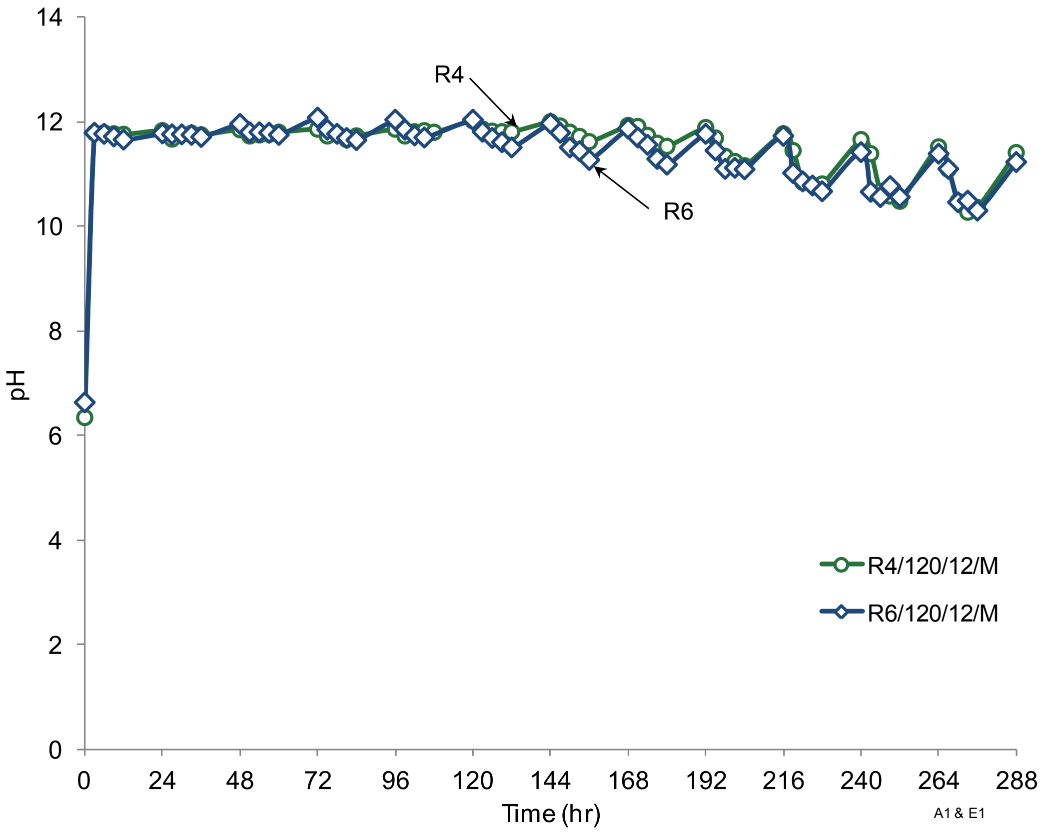
5.3.3 pH of water collected during R4 and R6 EO tests



(a)



(b)



(c)

Figure 5.8: Variation in pH of water collected during EO test with R4 and R6 electrode configuration at voltage gradient of (a) 80V/m, (b) 100V/m and (c) 120V/m

Figure 5.8 presents the variation in pH of water collected during R4 and R6 EO tests. The water collected overnight in the drainage well after preparation of the test tank was removed before the test started. The pH of the water was recorded as the pH of water before the application of DC

Figure 5.8(a) shows the variation in pH of water collected during EO tests with voltage gradient of 80V/m. The pH of the water collected before the start of the test was 5.55 and 5.45 for R4 and R6 respectively. With the application of voltage gradient of 80V/m, pH of water collected at 3hr shows significant increase. At 3hr, pH of the water collected is 11.23 and 11.22 for R4 and R6 respectively. The increase in pH of water collected reflects the electrolysis process at the cathode and generation of hydroxides. In the R4 electrode configuration test, the pH of water collected ranges from 9.85 to 11.7. In the R6 electrode configuration test, the pH of water collected ranges from 9.76 to 11.31.

Figure 5.8(b) shows the variation in pH of water collected during EO tests with voltage gradient of 100V/m. The pH of the water collected before the start of the test was 5.59 and 6.21 for R4 and R6 respectively. By 3hr during the test, pH of the water collected increases to 11.97 and 11.95 for R4 and R6 respectively. Marginal difference is observed in the pH of water collected from the R4 and R6 tests. pH of the water collected for the R4 and R6 tests show reduction with time from 216hr onward. Highest recorded pH is 12.13 and 12.11 for R4 and R6 respectively. At the end of the test, pH of the water collected is 10.13 and 10.01 for R4 and R6 test respectively. The reduction in pH of water collected may indicate the reduction in electrolysis process at the cathode where less hydroxides are generated, hence lowering pH of water collected. The reduction in electrolysis process could be attributed to the reduction in moisture content of the peat.

Figure 5.8(c) shows the variation in pH of water collected during EO tests with voltage gradient of 120V/m. Initial pH of water before the start of the test was 6.34 and 6.63 for R4 and R6 respectively. In the R4 test, pH of the water collected ranges from 10.27 to 12.02. At the end of the test, pH of the water collected was 11.41. In the R6 test, pH of the water collected ranges from 10.30 to 12.08. At the end of the test, pH of the water collected is 11.23. Marginal difference is observed in the pH of water collected in the R4 and R6 tests. A very gradual reduction in pH with time can be observed from 192hr onward in R4 and R6 tests.

All the EO tests exhibit a slight reduction in pH for water collected during the day. This could be attributed to the 3hr pumping intervals during the day, where the accumulation of hydroxide ions near the cathode is reduced with the frequency of water removal. However, as the water is left overnight in the drainage well, the accumulation of hydroxide ions is higher, hence the higher pH of water collected for the first collection of each day. For the R4 tests with voltage gradient of 80V/m, 100V/m and 120V/m, lowest pH of water collected is observed in the test with voltage gradient of 80V/m. This is attributed to the lower electrochemical reactions during electrolysis of water at lower voltage gradient. No significant difference in pH of water collected is observed in the R4 test with voltage gradient of 100V/m and 120V/m. In the R6 tests with voltage gradient of 80V/m, 100V/m and 120V/m, the test with voltage gradient of 80V/m also shows a lower pH range in water collected. For the R6 tests with voltage gradient of 100V/m and 120V/m, only marginal differences in pH of water collected is observed.

5.4 Voltage and current in peat during R4 and R6 EO tests

5.4.1 Voltage in peat during R4 and R6 EO tests with voltage gradient of 80V/m

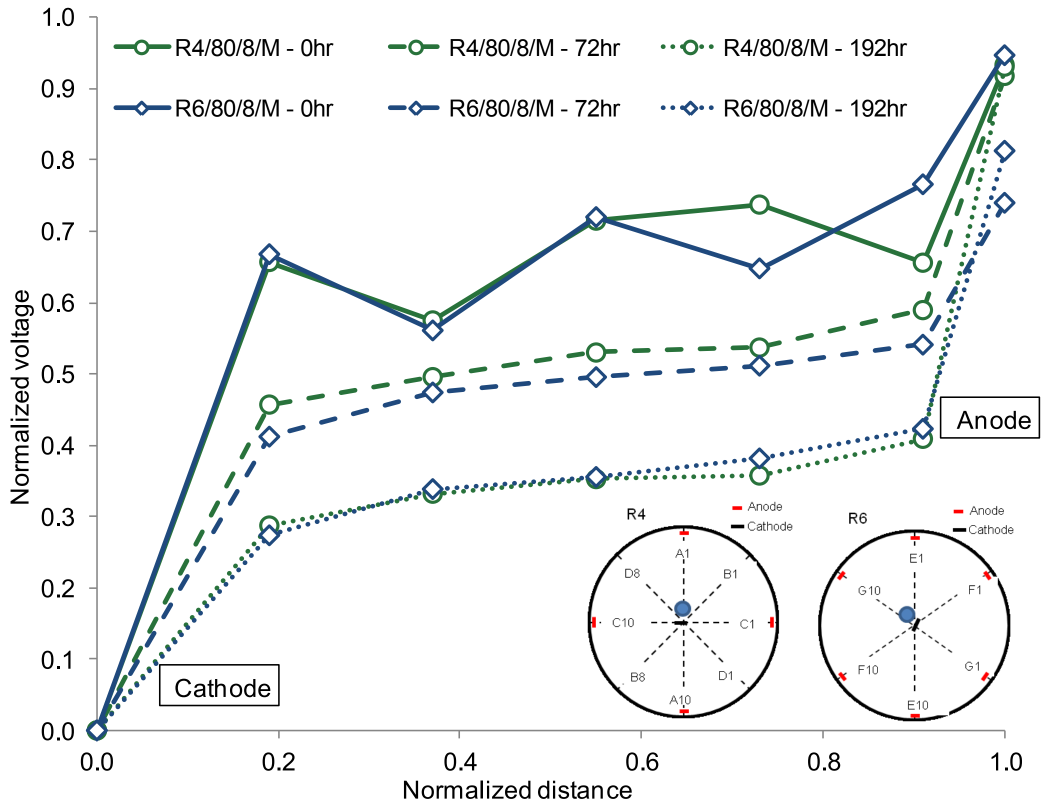


Figure 5.9: Variation of normalized measured voltage transmitted through peat with time during EO tests with R4 and R6 electrode configuration at voltage gradient of 80V/m

Figure 5.9 shows the variation in normalized measured voltage with time of the representative section along A1-A5 of the R4 test and E1-E5 of the R6 test during EO tests with voltage gradient of 80V/m. The variation in measured voltage with time for the other anodes of the R4 test is shown in the Appendix as A 11 and A 12. The variation in measured voltage with time for the other anodes of the R6 test is shown in the Appendix as A 13 to A 15.

For EO tests with radial electrode configurations, voltage losses is observed near the electrodes, similar to that seen in the small and large scale 1D tests presented in the previous chapter. The voltage loss is observed as the voltage drop between the cathode and the first voltage probe (0.19 normalized distance) as well as between the last voltage probe (0.91 normalized distance) and the anode.

Initial voltage loss near the cathode and anode of the R4 test is 66% and 34% respectively. For the R6 test, initial voltage loss is 67% and 23% near the cathode and anode respectively. The higher voltage loss near the cathode compared to that near the anode of the R4 and R6 test was observed in the large scale grid electrode configuration tests (Section 4.2.3). The higher loss is attributed to reduction in contact between peat and cathode due to the drainage well. Initial voltage transmitted through peat along the representative sections could not be determined due to fluctuation in measured voltage. In the R4 test, only two anodes did not show voltage fluctuation. For those two anodes, initial voltage transmitted through peat between the first and last voltage probe is 11% and 15%. In the other anodes of the R6 test, initial voltage transmitted through peat ranges from 9 to 20%.

As the test progressed, voltage losses in the R4 and R6 tests show reduction near the cathode and increment near the anode. Similar trend is observed for the other sections of the R4 and R6 tests. By 72hr in the R4 test, voltage loss near the cathode and anode is 46% and 41% respectively. This translates to 13% voltage transmitted through peat. The other three anodes recorded voltage transmitted ranging from 12 to 44%. At 72hr, voltage loss near the cathode and anode of the R6 test is 41% and 46% respectively. Voltage transmitted through peat is 13%. For the five other anodes of the R6 test, voltage transmitted through peat ranges from 12 to 22%.

At the end of the test (192hr), voltage loss near the cathode reduces further while voltage loss near the anode continues to show increment for both R4 and R6 tests. In the R4 test, voltage loss is 29% and 59% near the cathode and anode respectively. This resulted in 12% voltage transmitted through peat. For the three other anodes of the R4 test, voltage transmitted through peat ranges from 11 to 26%. The anode near A10 of the R4 test consistently shows the highest voltage transmitted through peat. This might be due to the alignment of the cathode and the anode of the test setup. The cathode is parallel to the anode near A10, without any obstruction in between. Hence both cathode and anode (A10) is in full contact with peat. Higher contact area between the cathode and peat might result in lower voltage losses and the development of a more uniform electric field. This coincides with the lowest voltage loss recorded between the cathode and anode (A10). For the area between the cathode and anode near A1, higher voltage loss and subsequent lower voltage transmitted is recorded.

For the R6 test, at 192hr, voltage loss near the cathode and anode is 27% and 58% respectively, resulting in 15% voltage transmitted through peat. For the other five anodes in the R6 test, voltage transmitted ranges from 13 to 23%. In the R6 test, the effect of reduced contact of peat due to drainage well near the central cathode is observed as well. This is seen as the higher voltage loss near the cathode for two anodes (near E1 and G10), resulting in lower voltage transmitted through peat. Compared to the R4 electrode configuration test, voltage transmitted through peat in the R6 electrode configuration test shows lower variation.

In both the R4 and R6 tests, voltage loss near the anode increases with time while the voltage loss near the cathode reduces with time. The increment of voltage loss near the anode is a possible indication of the direction of EO flow from the anode toward the cathode. With the movement of water away from the anode, reduction in moisture content in the vicinity of the anode occurs. The reduction in moisture content subsequently reduces the conductivity of peat. Another possible factor for the increase in voltage loss might be the reduction of voids in peat as water is removed and the peat settled. The reduction in voids might lead to reduction in porosity of peat. Reduction in the porosity of peat increases resistivity (Huat *et al.* 2014) and lowers the conductivity of peat. The comparatively lower voltage loss near the cathode is attributed to the migration of water toward the cathode, increasing the conductivity in the vicinity of the cathode.

5.4.2 Voltage in peat during R4 and R6 EO tests with voltage gradient of 100V/m

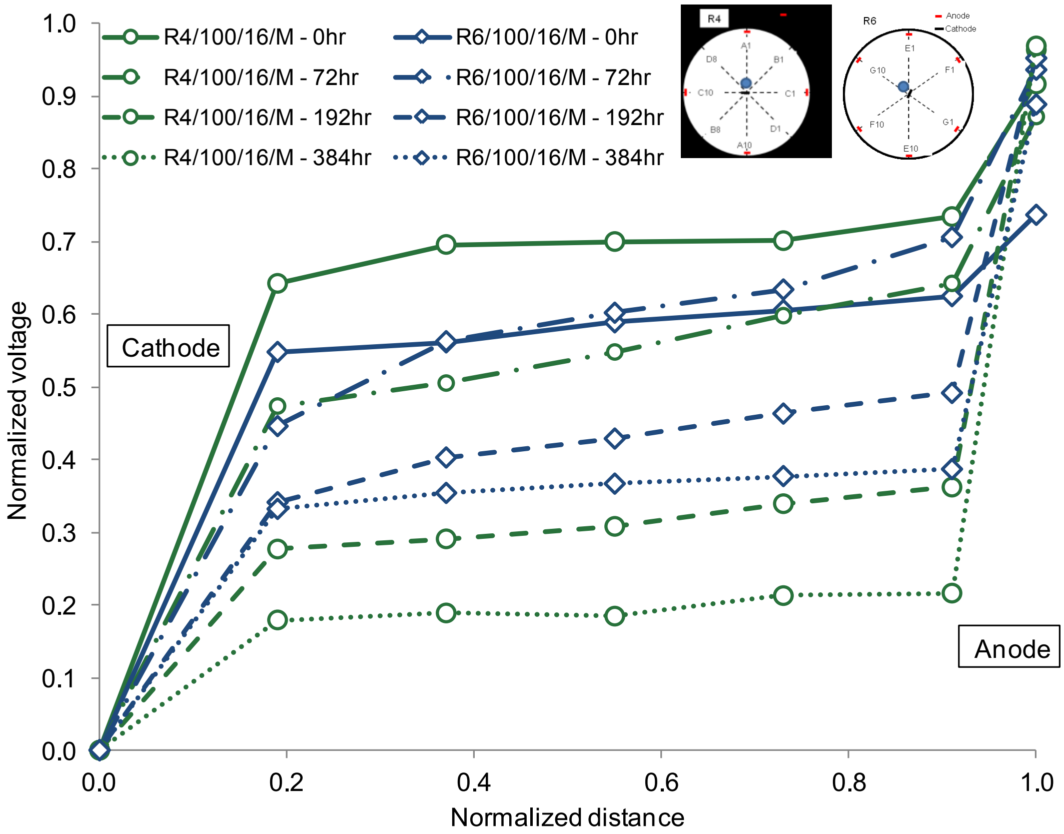


Figure 5.10: Variation of normalized measured voltage transmitted through peat with time during EO tests with R4 and R6 electrode configuration at voltage gradient of 100V/m

Figure 5.10 shows the variation in normalized measured voltage with time for the representative section along A1-A5 of the R4 test and E1-E5 of the R6 test during EO tests with voltage gradient of 100V/m. The variation in measured voltage with time for the other anodes of the R4 electrode configuration is shown in the Appendix as A 31 and A 32. The variation in measured voltage with time for the other anodes of the R6 electrode configuration is shown in the Appendix as A 33 to A 35.

At the start of the test, the voltage loss in the R4 test is 64% and 27% near the cathode and anode respectively. Voltage transmitted through the peat between the first and last voltage probes in the R4 test is 9%. For the other anode along Grid A, voltage transmitted is 8% while the voltage transmitted along Grid C could not be calculated due to voltage fluctuation. For the R6 test, initial voltage loss near the cathode is 55% while the voltage loss near the anode is 37%. However, the voltage measurements may not be accurate due to unstable DC supply from the laboratory benchtop power supply. The faulty power supply was replaced at 48hr.

At 72hr, voltage losses in the R4 and R6 tests show reduction near the cathode and increment near the anode. Similar trend is observed in the R4 and R6 tests with voltage gradient of 80V/m. By 72hr, voltage loss near the cathode and anode of the R4 test is 47% and 36% respectively. This translates to 17% voltage transmitted through peat. This is 4% higher than that of the same section in the R4 test with voltage gradient of 80V/m. At the three other anodes of the R4 test, voltage transmitted ranges from 19 to 29%. The highest voltage loss along A1-A5 in the R4 test might be due to the drainage well between the central cathode and the anode at A1. In the R6 test, voltage loss near the cathode and anode is 45% to 29%, with 26% voltage transmitted. This is larger than the voltage transmitted through peat for the R4 test. For the R6 test, the voltage transmitted is also higher than that of the test with voltage gradient of 80V/m. The voltage transmitted at the other anodes in the R6 test ranges from 20 to 41%.

After 192hr of the tests, voltage loss near the cathode continues to decrease while voltage loss near the anode continues to increase. In the R4 test, voltage loss near the anode is 64% and voltage loss near the cathode is 28%. Voltage transmitted in the peat decreases to 8%, which is lower than that at 192hr of the test with voltage gradient of 80V/m along the representative section. At the other anodes, voltage transmitted ranges from 8 to 14%, which is also significantly lower than that of test with voltage gradient of 80V/m. For the R6 test, voltage loss is 34% and 51% near the cathode and anode respectively. Voltage transmitted is 15%. At the other anodes, voltage transmitted ranges from 11 to 20%. The voltage transmitted at 192hr of the R6 test with voltage gradient of 100V/m show similar range to that of the test with voltage gradient of 80V/m.

At the end of the test, at 384hr, voltage loss near the cathode of the R4 test further decreases to 18% while the voltage loss near the anode increases to 78%. As a result, only 4% voltage is transmitted through the peat. For the other three anodes, the voltage transmitted ranges from 4 to 5%. In the R6 test, voltage loss near the cathode and anode is 33% and 61% respectively, with 6% voltage transmitted through the peat. For the other five anodes of the R6 test, voltage transmitted through peat ranges from 8 to 13%.

Both tests with R4 and R6 electrode configurations show voltage losses near cathode reducing with time and voltage losses near anode increasing with time. The percentage of voltage transmitted through peat in the R4 test underwent larger reduction with time. In comparison, the R6 test shows a more gradual reduction in voltage transmitted through peat with higher range of voltage transmitted through peat.

5.4.3 Voltage in peat during R4 and R6 EO tests with voltage gradient of 120V/m

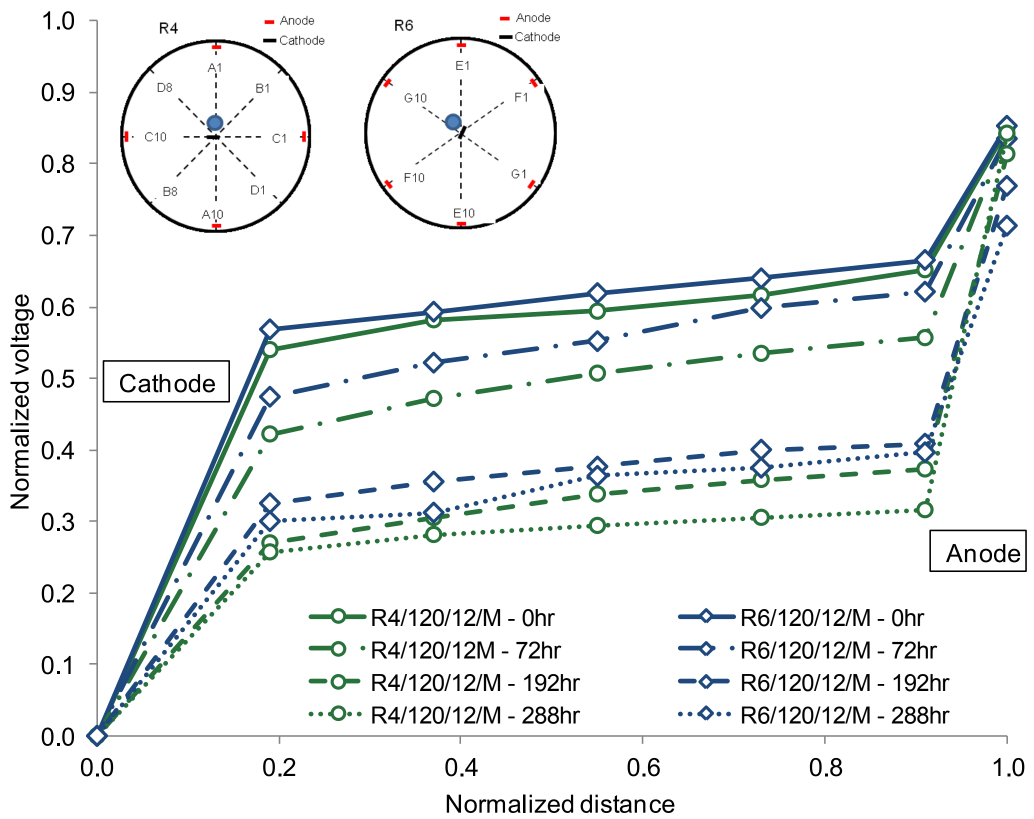


Figure 5.11: Variation of normalized measured voltage transmitted through peat with time during EO tests with R4 and R6 electrode configuration at voltage gradient of 120V/m

Figure 5.11 shows the variation in normalized measured voltage with time for the representative section along A1-A5 of the R4 test and E1-E5 of the R6 test during EO tests with voltage gradient of 120V/m. The variation in measured voltage with time for the other anodes of the R4 electrode configuration is shown in the Appendix as A 51 and A 52. The variation in measured voltage with time for the other anodes of the R6 electrode configuration is shown in the Appendix as A 53 to A 55.

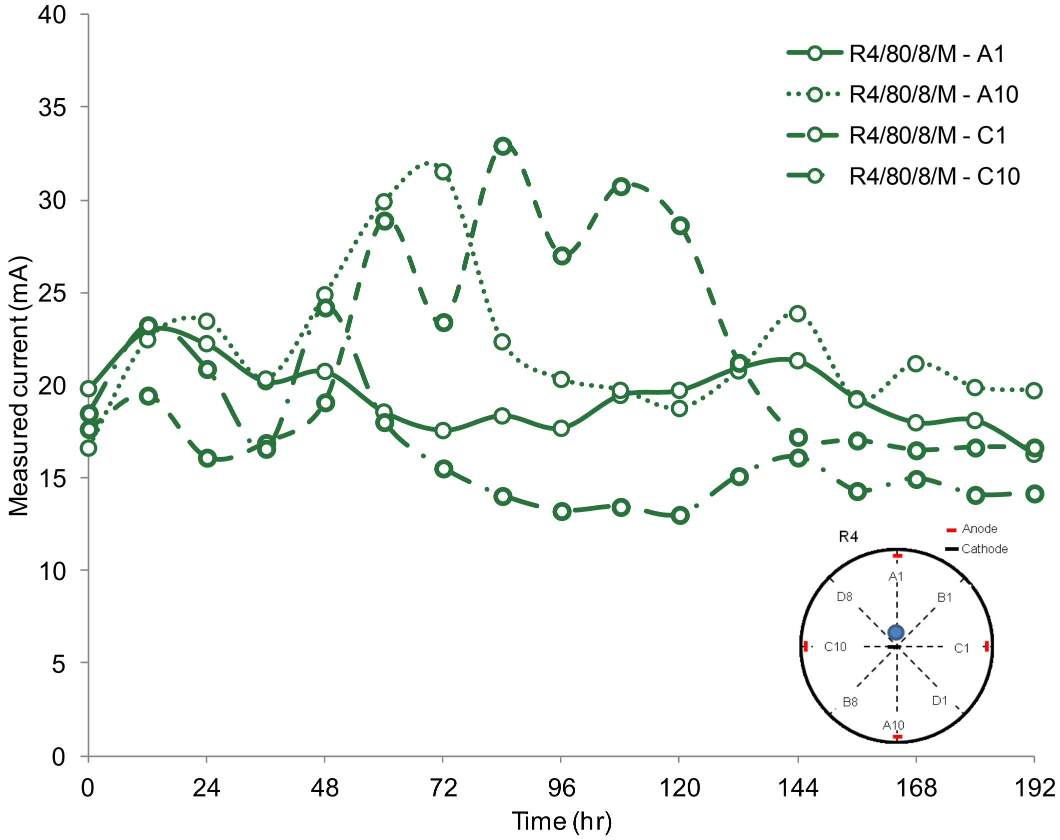
The trend in voltage variation through peat in this set of test is similar to earlier tests with voltage gradients of 80V/m and 100V/m. However one notable difference is the lower measured voltage at the electrode acting as the anode. In both the R4 and R6 tests, the anodes recorded lower than 90% of the supplied voltage. For the tests with 80V/m and 100V/m, the voltage measurements at the anode were higher than 90% of the supplied voltage. Some loss in voltage is expected at the electrodes due to resistance of the electrodes. However, in the tests with 120V/m, it appears that voltage gradient of 120V/m resulted in higher resistances at the electrodes with approximately 10% additional losses.

In the R4 test, initial voltage loss near the cathode and anode is 54% and 35% respectively. The initial voltage transmitted between the first and last voltage probe is 11%. The other three anodes of the R4 test recorded initial voltage transmitted ranging from 12 to 13%. The initial voltage transmitted shows similar ranges to that of tests with voltage gradients of 80V/m and 100V/m. In the R6 test, initial voltage loss near the cathode and anode is 57% and 33% respectively. The initial voltage transmitted through the peat is 10%. At the other five anodes of the R6 test, initial voltage transmitted ranges from 8 to 21%. The range of initial voltage transmitted also shows similarity to that of the test with voltage gradient of 80V/m.

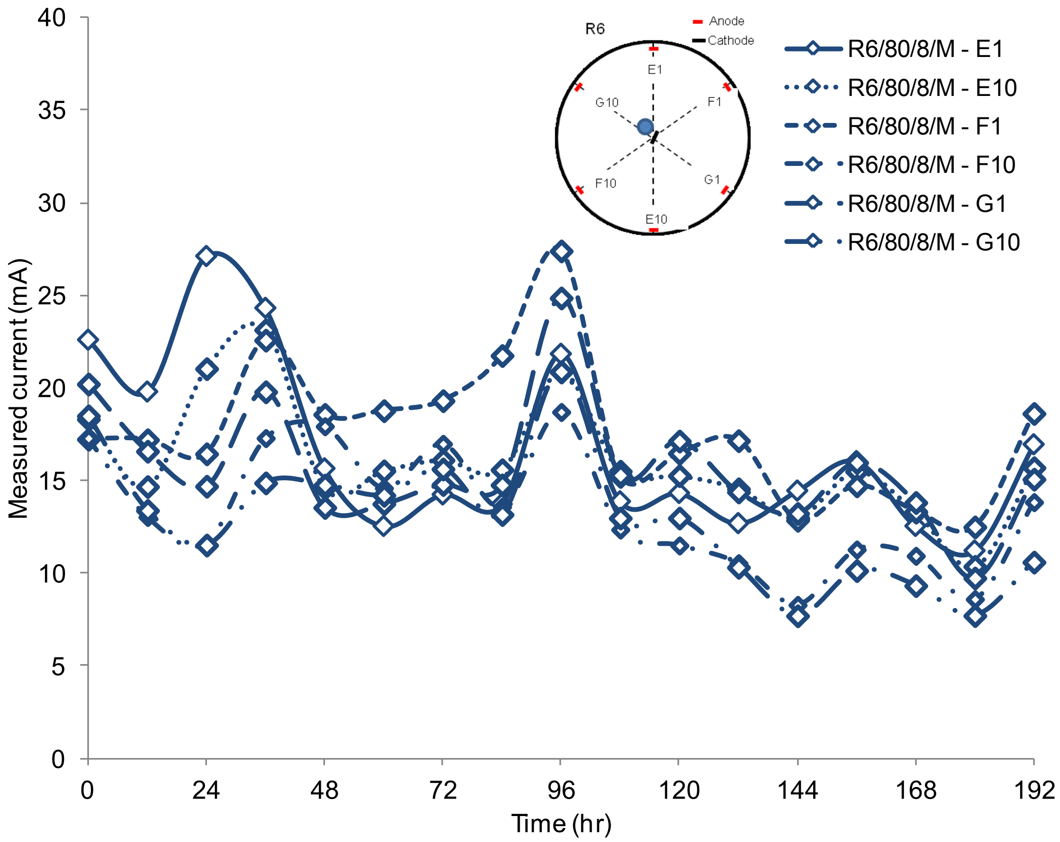
At 72hr, voltage loss in the R4 test has reduced to 42% and 44% near the cathode and anode respectively. Voltage transmitted through peat increases to 13%. This is similar to that of test with voltage gradient of 80V/m but lower than that of test with voltage gradient of 100V/m. For the other three anodes, the voltage transmitted through peat ranges from 11 to 24%. For the R6 test, voltage loss is 47% and 38% near the cathode and anode respectively, with 15% voltage transmitted through peat. This is also similar to that of the test with voltage gradient of 80V/m and lower than that of the test with voltage gradient of 100V/m. At the other five anodes, voltage transmitted ranges from 17 to 28%. At the end of the test at 288hr, voltage transmitted through peat in the R4 test ranges from 6 to 11%. The R6 test also show similar reduction in voltage transmitted, ranging from 8 to 11%.

For this set of tests, the effect of the drainage well reducing contact between cathode and anode is seen at the anode near A1 of the R4 test. The anode near A10 also show lower voltage transmitted. Without the drainage well between the cathode and anode A10, the lower voltage transmitted might be due to non-uniform electric field occurring in the peat as a result of the alignment of the central cathode to anode A10. For the R6 test, lower voltage transmitted is recorded for anodes near E1 and G10. This is attributed to the reduction in cathode and peat contact due to the drainage well, discussed earlier.

5.4.4 Current in peat during R4 and R6 EO tests with voltage gradient of 80V/m



(a)



(b)

Figure 5.12: Variation in measured current with time in (a) R4 and (b) R6 electrode configuration during EO tests with voltage gradient of 80V/m

Figure 5.12(a) shows the variation in measured current with time in test with R4 electrode configuration with voltage gradient of 80V/m. Current measurements were taken by introducing a multimeter in series to the electrical circuit. No significant trend is observed in the measured currents of the R4 test. Initial current ranges from 17 to 20mA. Fluctuation in current is observed at three anodes while the measured current near A1 shows a fairly constant current throughout the test. Highest current is 33mA, at the anode near C1. The current in the R4 test ranges from 13 to 33mA. The currents near A1 and C10 show lower magnitudes. This might be due to the lower voltage transmitted through peat for the respective anodes seen in earlier section.

Figure 5.12(b) shows the variation in measured current for the six anodes in the R6 test. The measured current of the six anodes show similar trends. Initial measured current ranges from 17 to 23mA, which is similar to the initial measured currents of the R4 test. Between 0 to 48hr, the measured currents show decrease followed by an increase. Measured currents between 0 to 48hr range from 11 to 27mA. Less fluctuation in measured currents in observed between 48 to 84hr where five anodes recorded measured currents ranging from 12 to 18mA, while one anode shows a higher range from 18 to 22mA. At 96hr, a sharp increase is observed with magnitudes ranging from 19 to 27mA. Following that, the currents decrease to a lower range from 8 to 17mA. At the end of the test, the currents increase to range from 11 to 19mA. Relatively lower current magnitudes were recorded for G10. This might be due to the lower voltage transmitted for the respective anode. However, the measured current near E1 does not reflect the lower voltage transmitted at the anode.

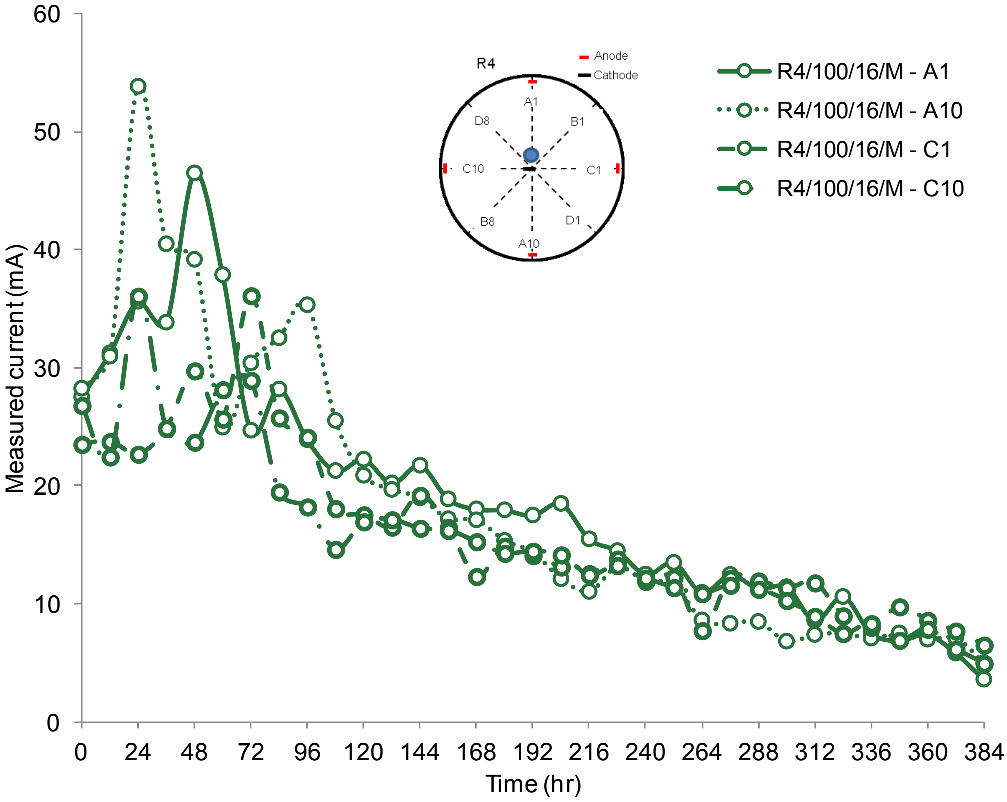
The overall measured currents in the test with R4 electrode configuration show relatively higher magnitudes compared to the test with R6 electrode configuration. This is reflected in the higher voltage transmitted through peat in the R4 test. The measured currents in the R4 test did not show a significant trend whereas in the test with R6 electrode configuration, a noticeable decreasing trend with time is observed. The currents in the R6 test show less variation compared to the larger variation observed in the R4 test.

With the voltage and current data, an estimation of power consumption for the R4 and R6 electrode configuration tests can be calculated from:

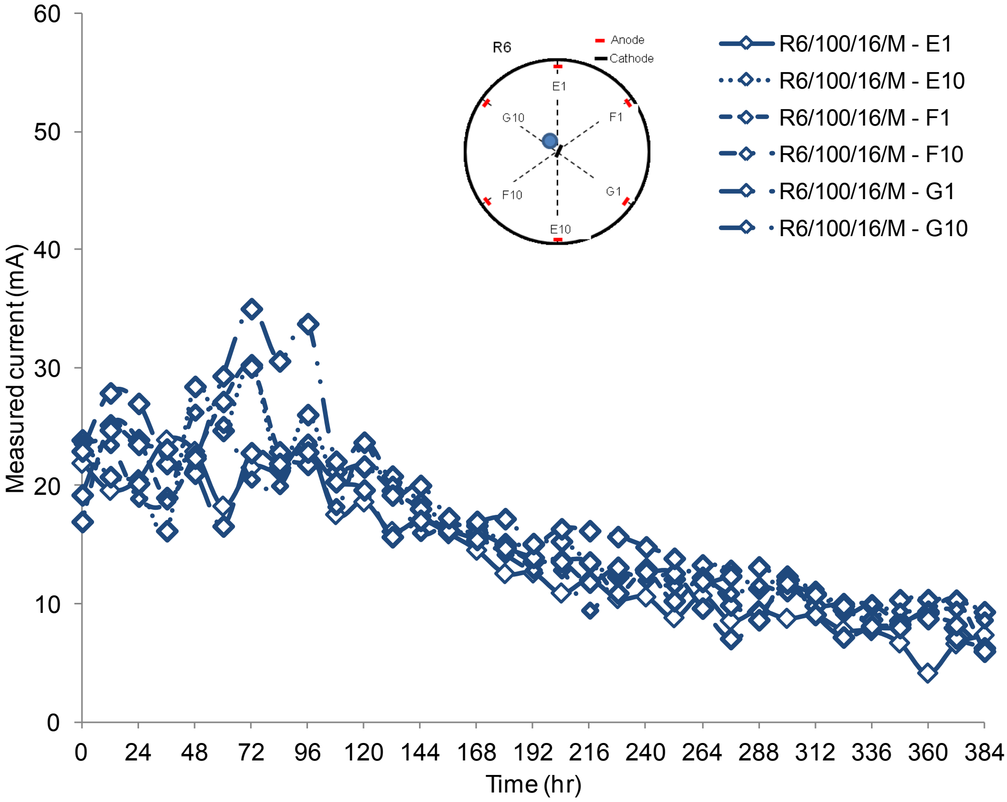
$$\boldsymbol{P = V \int_0^t I(t)dt} \qquad (5.1)$$

where P is the total power consumption, V is the voltage supplied, I is the measured current and t is the test duration. The total power consumption for the R4 and R6 electrode configuration test is 308Wh and 356Wh respectively. The power consumption for the R6 electrode configuration is 16% higher than the R4 configuration. However, the overall settlement of the R4 electrode configuration is 1.5% higher than that of the R6 electrode configuration. In terms of volume reduction, the estimated volume of reduction for R4 and R6 electrode configuration is 14% and 13% respectively. Estimation of volume reduction is based on the average settlement of each test. The power consumption per unit volume of wet peat is 2.6kWh/m^3 and 2.9kWh/m^3 for R4 and R6 respectively. In terms total volume of water collected, the power consumption per litre of water removed is 15.1Wh/ℓ and 17.5Wh/ℓ for R4 and R6 respectively.

5.4.5 Current in peat during R4 and R6 EO tests with voltage gradient of 100V/m



(a)



(b)

Figure 5.13: Variation in measured current with time in (a) R4 and (b) R6 electrode configuration during EO tests with voltage gradient of 100V/m

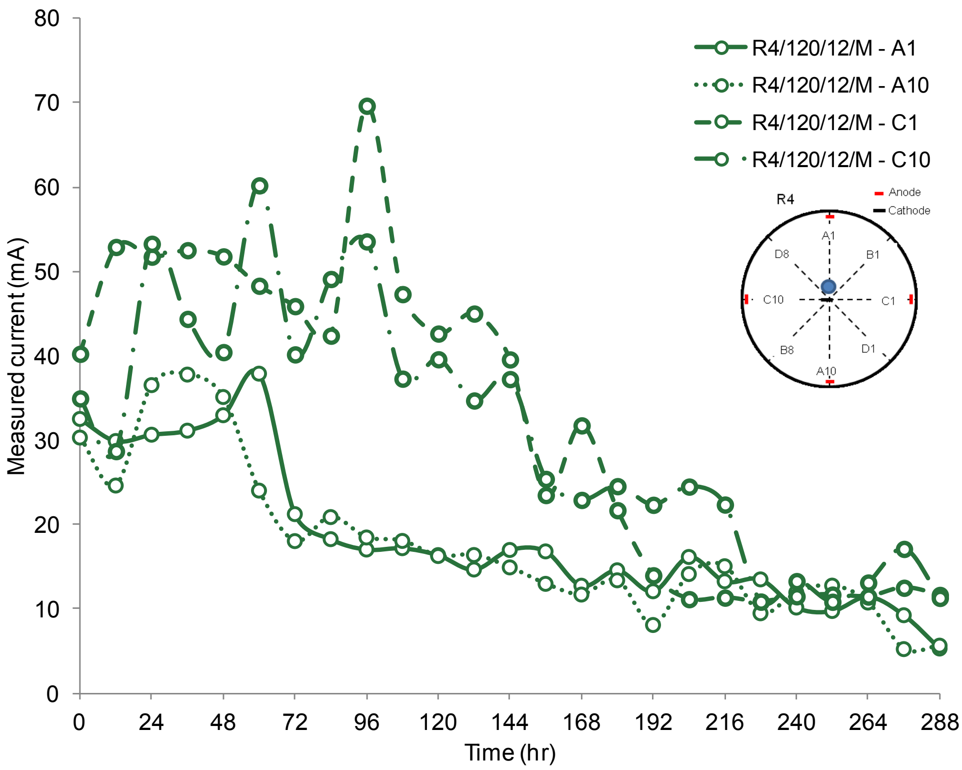
Figure 5.13(a) shows the variation in measured current in the R4 test with voltage gradient of 100V/m. Initial measured current ranges from 23 to 28mA. This is of a higher range than the initial current of the R4 test with voltage gradient of 80V/m. From the start of the test until 120hr, large fluctuation is observed. In this period of time, maximum measured current is 54mA near A10 at 24hr. The current near A10 does not reflect the higher voltage loss seen earlier. The current near A1 also shows relatively high magnitude at 48hr with 46mA. Between 72hr to 120hr, a gradual reduction in measured current is observed though fluctuations in the measured current continued. From120hr until the end of the test, all currents show less fluctuation and a more apparent reduction with time. At 120hr, the currents range from 17 to 25mA. By 192hr, the currents have decreased to range from 14 to 18mA. At the end of the test, current is low with values between 4 to 6mA. This is in agreement with the low voltage transmitted through the peat of the same test.

Figure 5.13(b) shows the measured current in the R6 test. Initial measured current ranges from 17 to 24mA. This is similar to the initial current in the R6 test with voltage gradient of 80V/m. Initial current of the R6 test with voltage gradient of 100V/m is lower than that of the R4 test. Fluctuation in current is also observed in the first 120hr of the test. Maximum current is recorded near G10 with 35mA at 72hr and 34mA at 96hr. These two peak currents are lower than the peak current of 54mA in the R4 test and they occurred after 24hr. In the R6 test, anode near G10 showed higher voltage loss earlier. However, the current near G10 does not reflect the higher voltage loss. For the R6 test, reduction in current is observed after 96hr. At 120hr, the currents range from 18 to 24mA. With gradual decrease with time, the currents range from 6 to 8mA at the end of the R6 test.

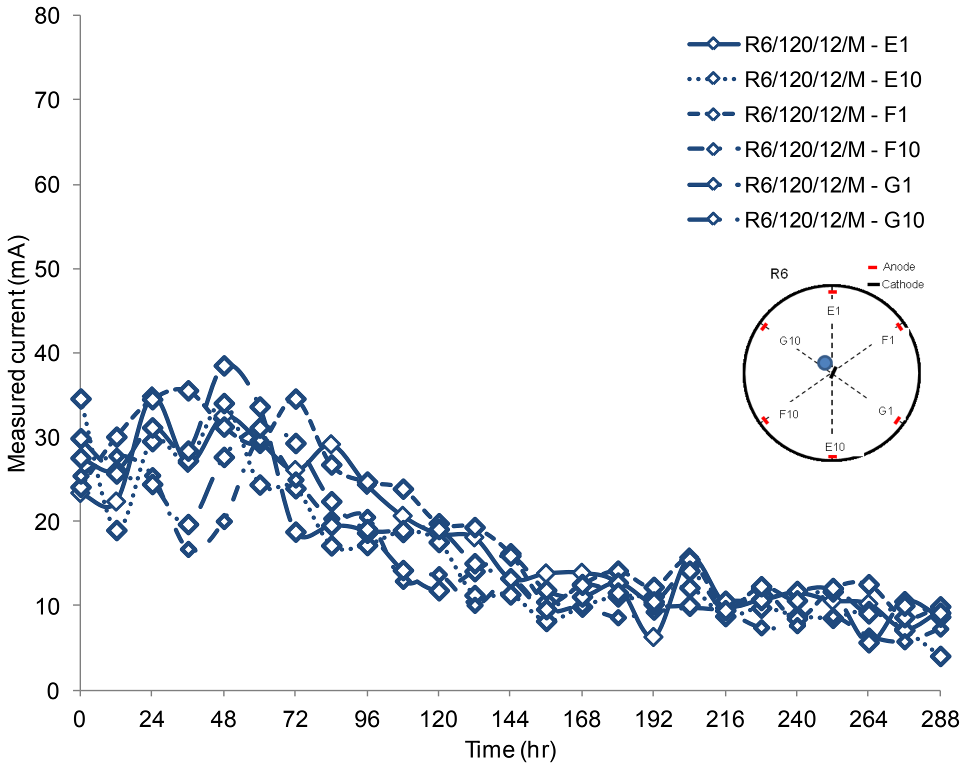
At the early stages of the test until 144hr, some of the currents in the R4 test show higher magnitude compared to the R6 test. At the later stages, both the R4 and R6 tests do not show significant variation in magnitude of measured currents. With the voltage gradient of 100V/m, the currents in peat show higher magnitudes compared to that of R4 and R6 tests with voltage gradient of 80V/m. Similar condition is observed in the small scale EO test, where higher voltage gradient resulted in higher current magnitude through peat.

The power consumption for the R4 and R6 electrode configuration test is calculated using Equation 5.1. The estimated total power consumption for the R4 and R6 test is 675Wh and 918Wh respectively. In this series of test, the voltage gradient was 100V/m and test duration was 16 days. The estimated total power consumption for the R6 test is 1.4 times that of the R4 test. The estimated volume reduction for R4 and R6 electrode configuration is 18% and 19% respectively. The power consumption per unit volume of wet peat is 6.1kWh/m^3 and 8.3kWh/m^3 for R4 and R6 respectively. The estimated power consumption of the R6 test is not consistent with the estimated volume reduction of the same test. The volume of water collected in the R6 test is 11% higher than the R4 test. In terms of volume of water collected, power consumption per litre of water removed is 22.6Wh/ℓ and 27.6Wh/ℓ for R4 and R6 respectively.

5.4.6 Current in peat during R4 and R6 EO tests with voltage gradient of 120V/m



(a)



(b)

Figure 5.14: Variation in measured current with time in (a) R4 and (b) R6 electrode configuration during EO tests with voltage gradient of 120V/m

Figure 5.14(a) shows the variation in measured current with time in the R4 test with voltage gradient of 120V/m. Initial current recorded ranges from 30 to 40mA. The measured current near A1 and A10 show lower magnitude throughout the test. This is reflected in the lower voltage transmitted through peat at the two respective anodes. Reduction in measured currents near A1 and A10 occur at 72hr with values of 21mA and 18mA respectively. Reduction in the measured currents near C1 and C10 is not observed until 156hr of the test. At 156hr, the measured current near C1 and C10 is 23mA and 25mA respectively. By the end of the test at 288hr, all measured currents range from 5.2 to 17mA. Highest recorded measured current is 70mA at 96hr. For the R4 test, voltage gradient of 120V/m resulted in the highest current.

Figure 5.14(b) shows the measured current in the R6 test with voltage gradient of 120V/m. Initial current at the start of the test ranges from 23 to 35mA. Large fluctuation in measured currents is observed for all six anodes until 96hr. In that period of time, measured currents range from 17 to 38mA. Reduction in measured current with time can be seen from 96hr onward. With the gradual decrease in measured current, the magnitude of current at the end of the test ranges from 4 to 10mA.

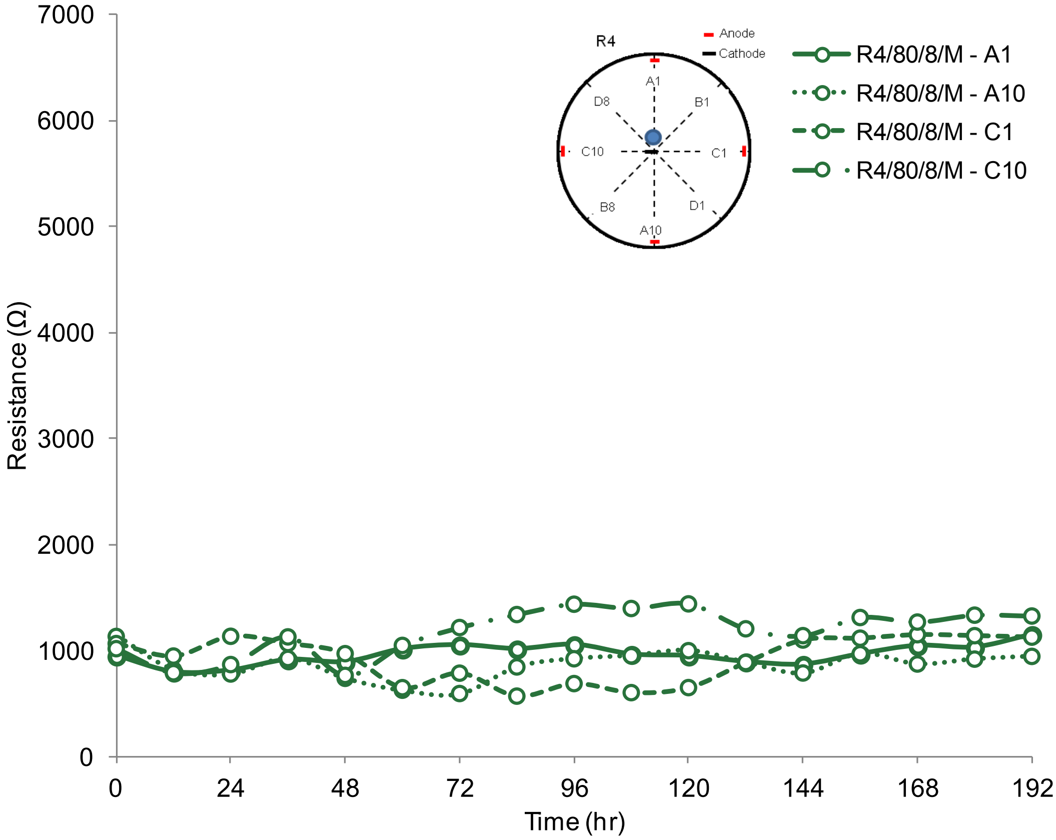
In the R4 and R6 test with voltage gradient of 120V/m, the measured current shows higher magnitudes than the respective tests with voltage gradient of 100V/m. In the R4 test, the increment in magnitude is more significant. Increase in voltage gradient resulted in higher current through the peat.

The energy consumption for the R4 and R6 electrode configuration tests are calculated using Equation 5.1. The estimated total energy consumption for the R4 and R6 test is 884Wh and 900Wh respectively. The estimated total energy consumption for the R4 and R6 test show marginal difference in this set of tests. The estimated volume reduction for the R4 and R6 tests is 14% and 13% respectively. This is similar to the volume reduction obtained in the R4 and R6 tests with voltage gradient of 80V/m and test duration of 8 days. Application of voltage gradient of 120V/m for 12 days did not result in higher volume reduction than the tests with voltage gradient of 80V/m. The power consumption per unit volume of wet peat is 7.6kWh/m^3 and 7.7kWh/m^3 respectively. In terms of volume of water collected, the power consumption per litre of water removed is 33.4Wh/ℓ and 34.9Wh/ℓ for R4 and R6 respectively.

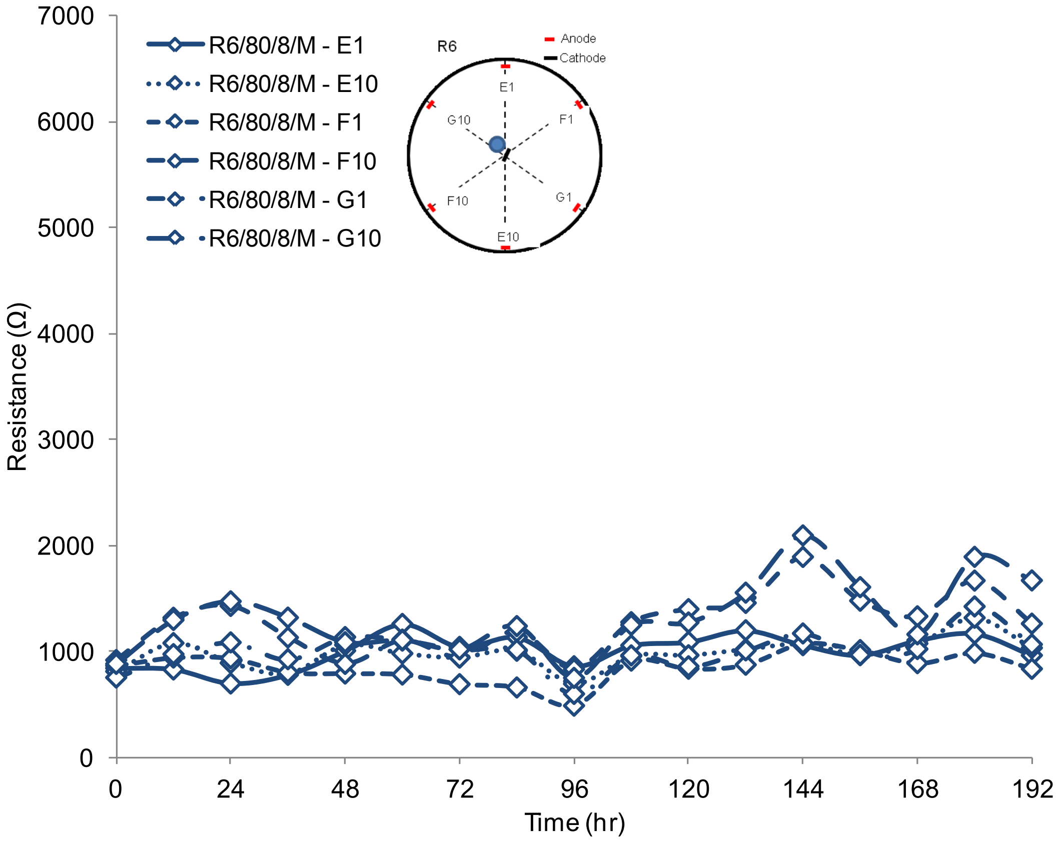
5.5 Resistance during EO of peat

Using the data of voltage and current obtained, the overall resistance of the electrical system is calculated. The sections between each anode and the cathode are further separated into three areas, namely the cathode region, the middle and the anode region. The cathode region is located between the cathode and the first voltage probe at 0.19 normalized distance from the cathode. The middle region is between the first and last voltage probe. The anode region is from the last voltage probe at 0.91 normalized distance and the anode.

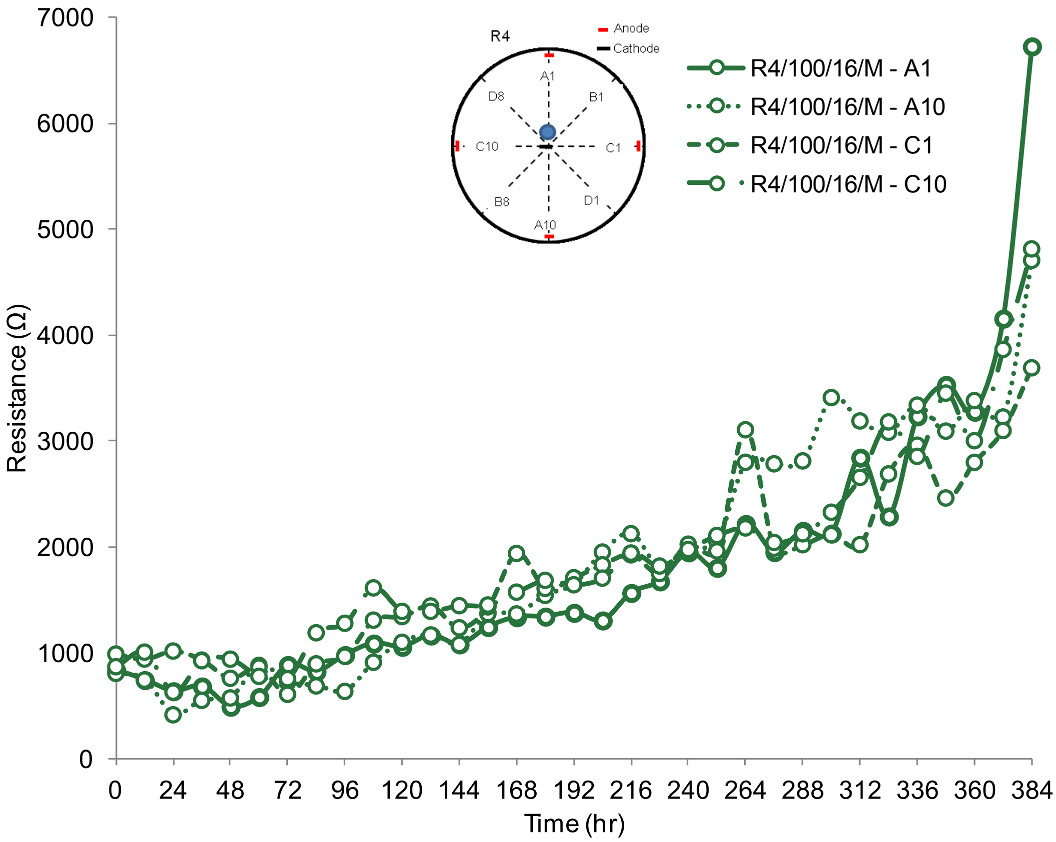
5.5.1 Overall resistance for R4 and R6 EO tests



(a)

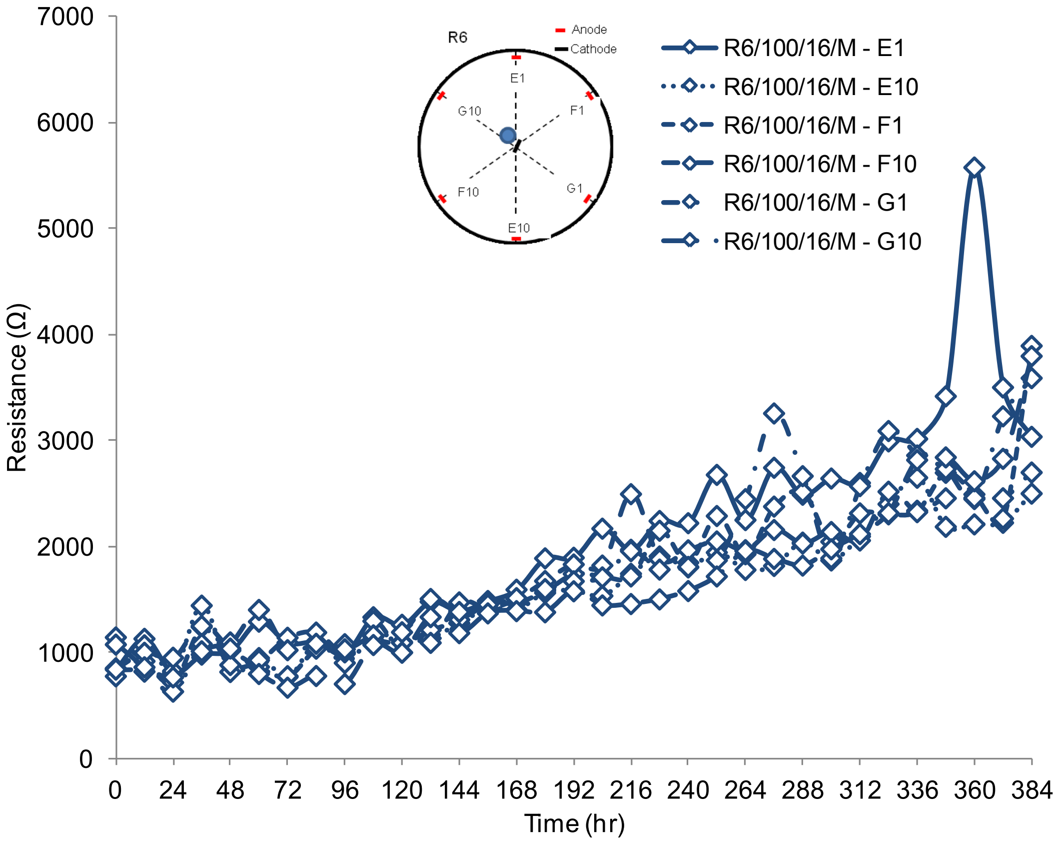


(b)



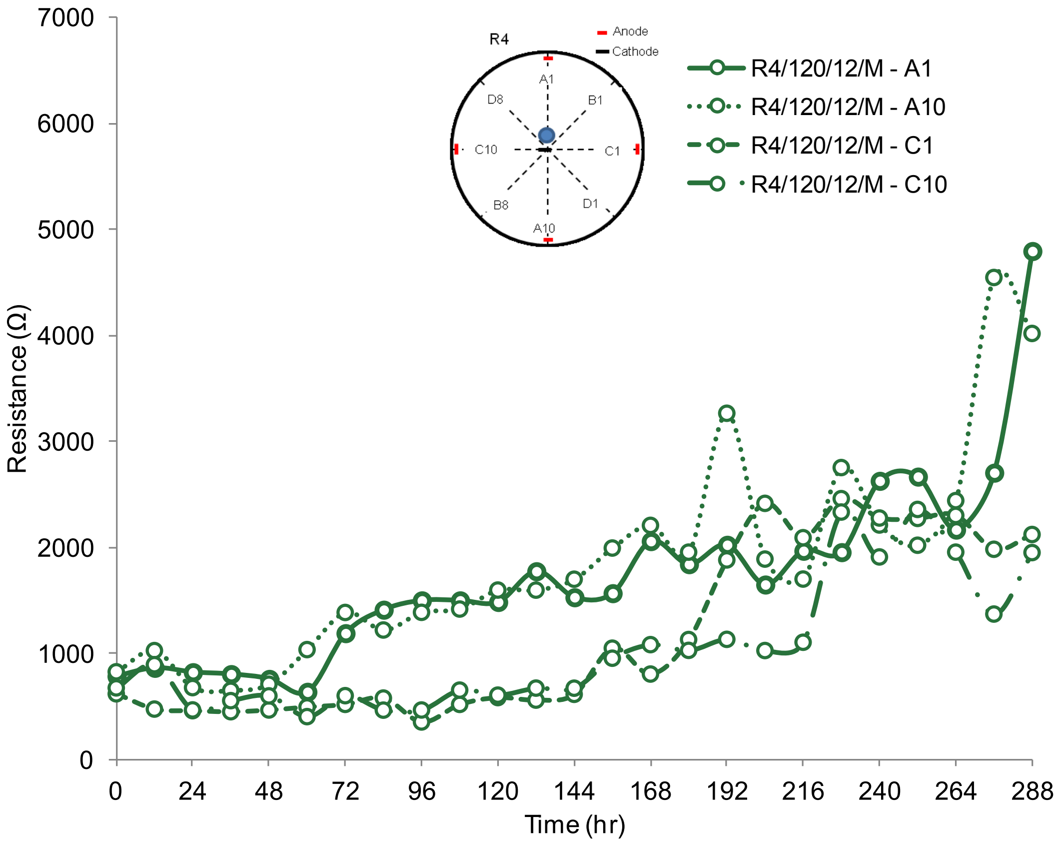
Resistance (Ω)
Time (hr)
R4
Anode
Cathode
A1
B1
C1
D1
A10
B8
C10
D8
R4/100/16/M - A1
R4/100/16/M - A10
R4/100/16/M - C1
R4/100/16/M - C10

(c)

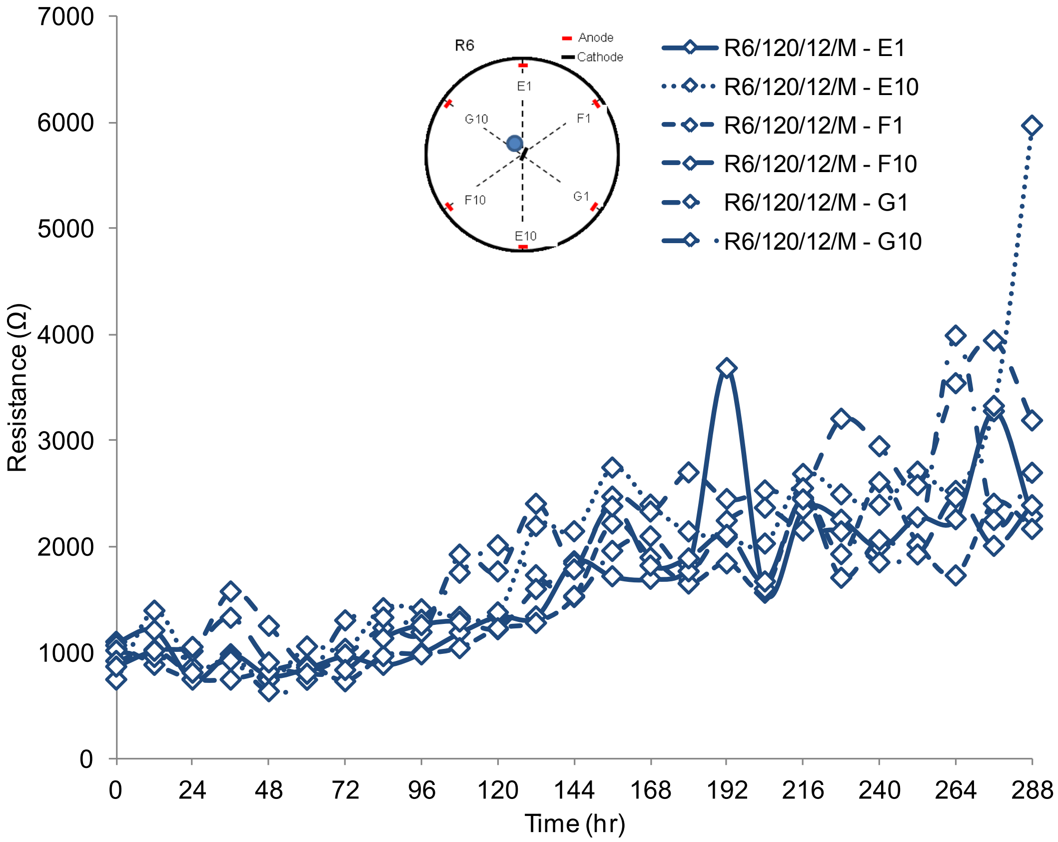


Resistance (Ω)
Time (hr)
R6
Anode
Cathode
E1
F1
G1
E10
F10
G10
R6/100/16/M - E1
R6/100/16/M - E10
R6/100/16/M - F1
R6/100/16/M - F10
R6/100/16/M - G1
R6/100/16/M - G10

(d)



(e)



(f)

Figure 5.15: Variation in overall resistance with time for (a) R4 and (b) R6 at 80V/m; (c) R4 and (d) R6 at 100V/m; and (e) R4 and (f) R6 at 120V/m

Figure 5.15(a) shows the variation in overall resistance with time in the R4 test with voltage gradient of 80V/m. Initial overall resistance ranges from 942 to 1129Ω. Large variation is observed in the overall resistance of the R4 test with overall resistance ranging from 565 to 1436Ω. At the end of the test, the overall resistances range from 941 to 1322Ω. Figure 5.15(b) shows the variation in overall resistance of the R6 test with voltage gradient of 80V/m. Initial overall resistance ranges from 750 to 914Ω. This is lower than the overall resistances of the R4 test. At 96hr, a drop in the overall resistances is observed with values ranging from 484 to 828Ω. Following that, the overall resistances start to show an increasing trend with peak value of 2092Ω at 144hr. The overall resistances near F1 and G10 show the highest resistance values at the later stage of the test. At the end of the test, the overall resistances range from 832 to 1667Ω.

No noticeable increasing or decreasing trend is observed in the overall resistance of the R4 test. This corresponds to the measured current of the same test, where no noticeable trend is observed. In the R6 test, a significant increasing trend in overall resistances can be seen after 120hr. From 120hr to 192hr, the overall resistances in R6 test show higher magnitudes in comparison to the R4 test. Peak overall resistance in R4 test is 1436Ω while peak overall resistance in R6 test is 2092Ω which is approximately 1.5 times the peak resistance in R4 test. The increase in overall resistance of the R6 test reflects the lower range of measured current through peat at the later stage of the test. The higher overall resistance of the R6 test is reflected in the lower volume of water collected and lower settlement of the same test.

Figure 5.15(c) presents the variation in overall resistance in the R4 test with voltage gradient of 100V/m. Initial overall resistance ranges from 800 to 983Ω. From 72hr onward, the overall resistances start to exhibit a gradual increase with time. By 192hr, the overall resistance has increased to range from 1375 to 1705Ω. At the end of the test, a maximum overall resistance of 6730Ω is recorded near A1. The other overall resistances at the end of the test are 3689Ω, 4705Ω and 4813Ω.

Figure 5.15(d) presents the variation in overall resistance with time in R6 test with voltage gradient of 100V/m. Initial overall resistance ranges from 833 to 1070Ω. A gradual increase with time is observed from 108hr onward. At 108hr, the overall resistances range from 1065 to 1291Ω. In the R4 test, the increasing trend in overall resistance is noticeable at 72hr, while for the R6 test, the increasing trend starts later, after 108hr. By 192hr, overall resistances in the R6 test have increased to range from 1573 to 1826Ω. The overall resistance near E1 shows a sudden increase to 5574Ω at 360hr of the test, which corresponds to a sudden drop in measured current at that time. At the end of the test, the overall resistances range from 2495 to 3793Ω.

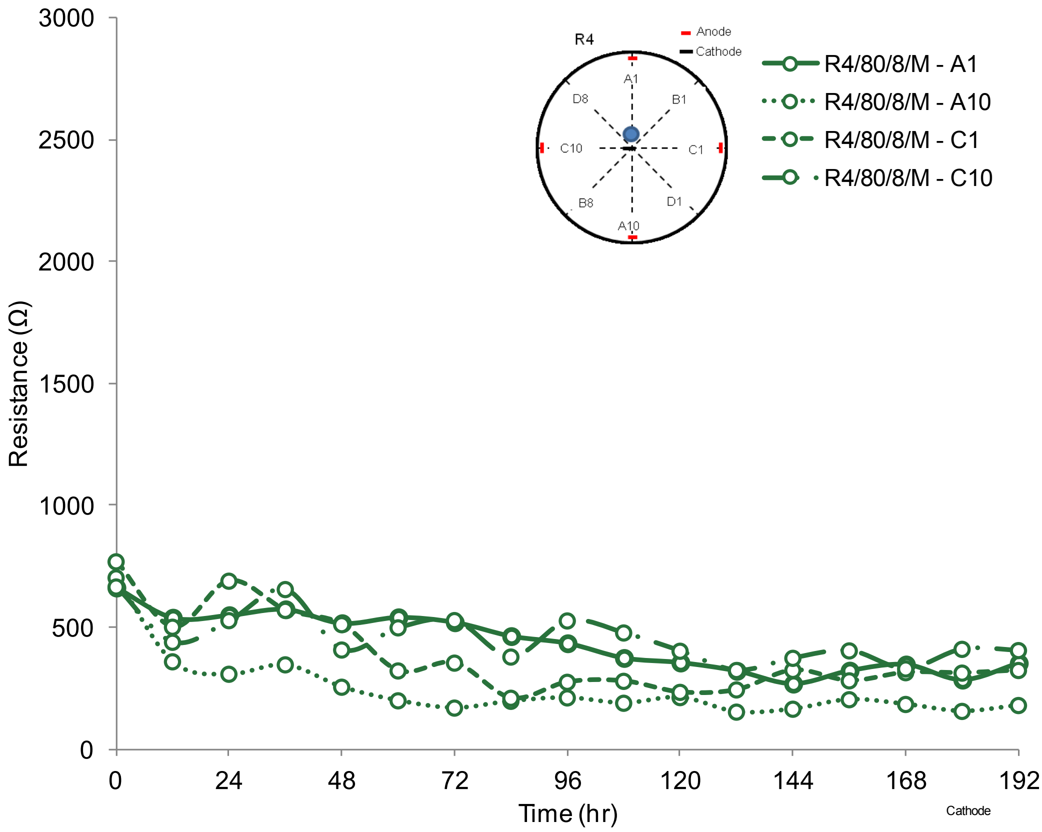
With voltage gradient of 100V/m, the R4 and R6 tests show significantly higher overall resistance at the later stages of the test. This is attributed to the removal of water from the peat and subsequent reduction in conductivity. The increase in overall resistance could be due to increase in resistance at the electrodes, discussed later. Higher range of resistance is observed in the R4 test, which is reflected in the lower volume of water collected and lower settlement of the same test.

Figure 5.15(e) shows the variation in overall resistance with time in R4 test with voltage gradient of 120V/m. Initial overall resistance upon application ranges from 614 to 823Ω. Comparatively higher overall resistance is observed near A1 and A10 between 60hr to 192hr. The values of overall resistance in this period of time range from 634 to 3264Ω. According to Ohm's law, the higher resistance is attributed to the lower current through peat. The overall resistance near C1 and C10 remained fairly low until 144hr, with values ranging from 349 to 890Ω. Overall resistance at the end of the test duration show a large variation between values obtained along Grid A and Grid C. The final overall resistance near A1 and A10 is high at 4799Ω and 4017Ω respectively. Near C1 and C10, the final overall resistance is 2119Ω and 1948Ω respectively, approximately half the overall resistance recorded along Grid A.

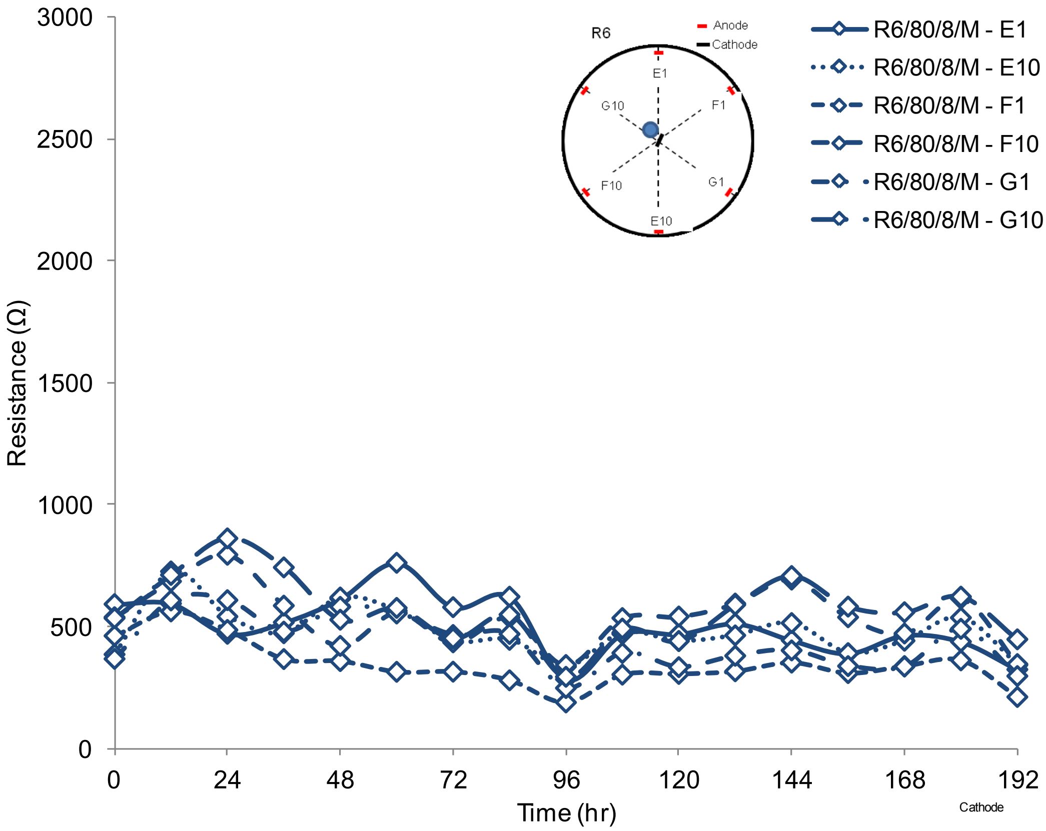
Figure 5.15(f) presents the variation in overall resistance with time in R6 test with voltage gradient of 120V/m. Initial overall resistance ranges from 740Ω to 1062Ω. The gradual increase in overall resistance with time is observed from 72hr onward. At 72hr, the range of overall resistance is between 723 to 1298Ω. By 192hr, overall resistance in the R6 test has increased to range from 1836 to 3681Ω. There is a sudden increase of resistance near E1 with 3681Ω at 192hr. At the end of the test, the resistance range from 2161 to 3186Ω. At 288hr, the highest resistance for R6 test is recorded at 5970Ω near E10.

Comparison of the range of resistances of the R4 and R6 test shows that the R6 test exhibited a higher range of overall resistance. This is reflected in the lower range of measured current of the R6 test. The volume of water collected and settlement of the R6 test is also lower than that of the R4 test.

5.5.2 Resistance at the cathode region of the R4 and R6 EO tests

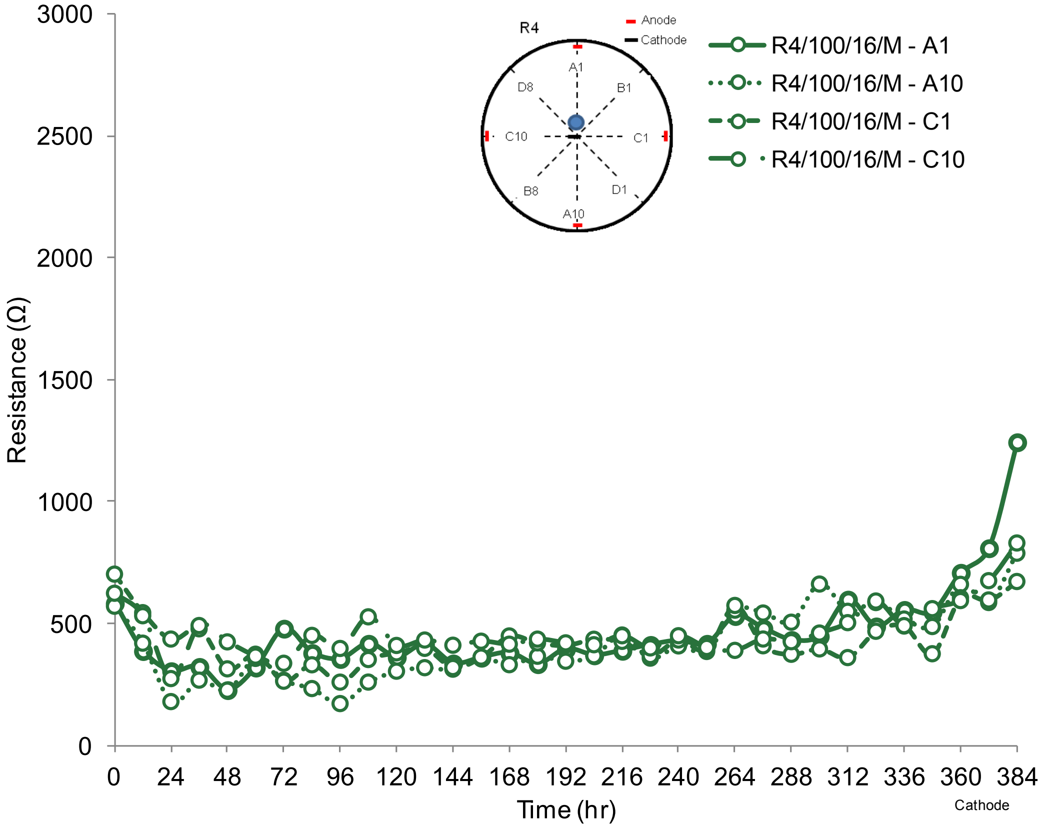


(a)



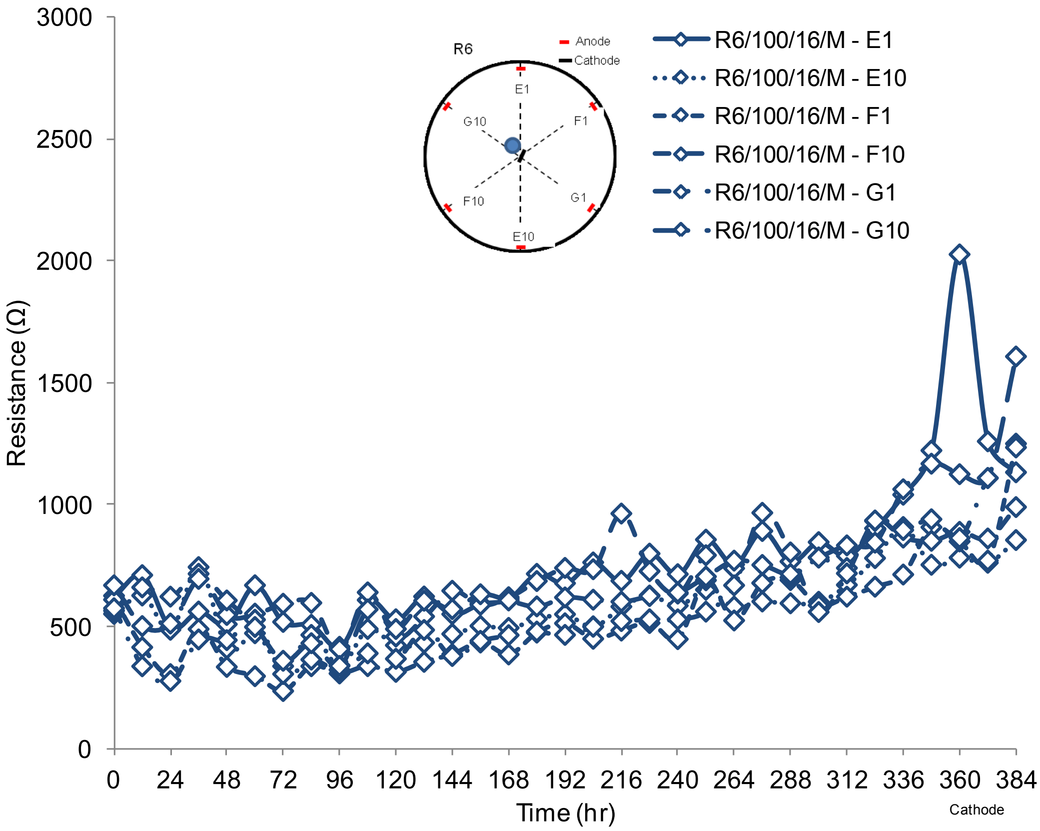
3000
2500
2000
1500
1000
500
0
Resistance (Ω)
R6
Anode
Cathode
E1
F1
G1
E10
F10
G10
R6/80/8/M - E1
R6/80/8/M - E10
R6/80/8/M - F1
R6/80/8/M - F10
R6/80/8/M - G1
R6/80/8/M - G10
0 24 48 72 96 120 144 168 192
Time (hr)
Cathode

(b)



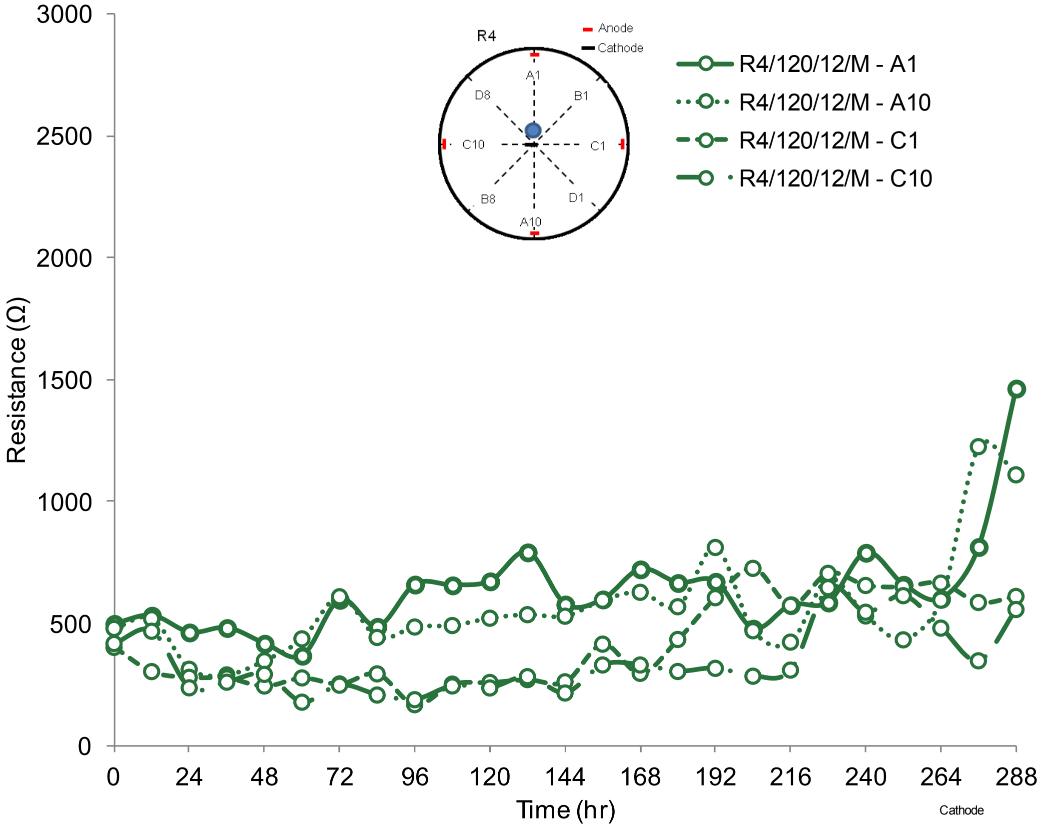
3000
2500
2000
1500
1000
500
0
Resistance (Ω)
R4
Anode
Cathode
A1
B1
C1
D1
A10
B8
C10
D8
R4/100/16/M - A1
R4/100/16/M - A10
R4/100/16/M - C1
R4/100/16/M - C10
0 24 48 72 96 120 144 168 192 216 240 264 288 312 336 360 384
Time (hr)
Cathode

(c)



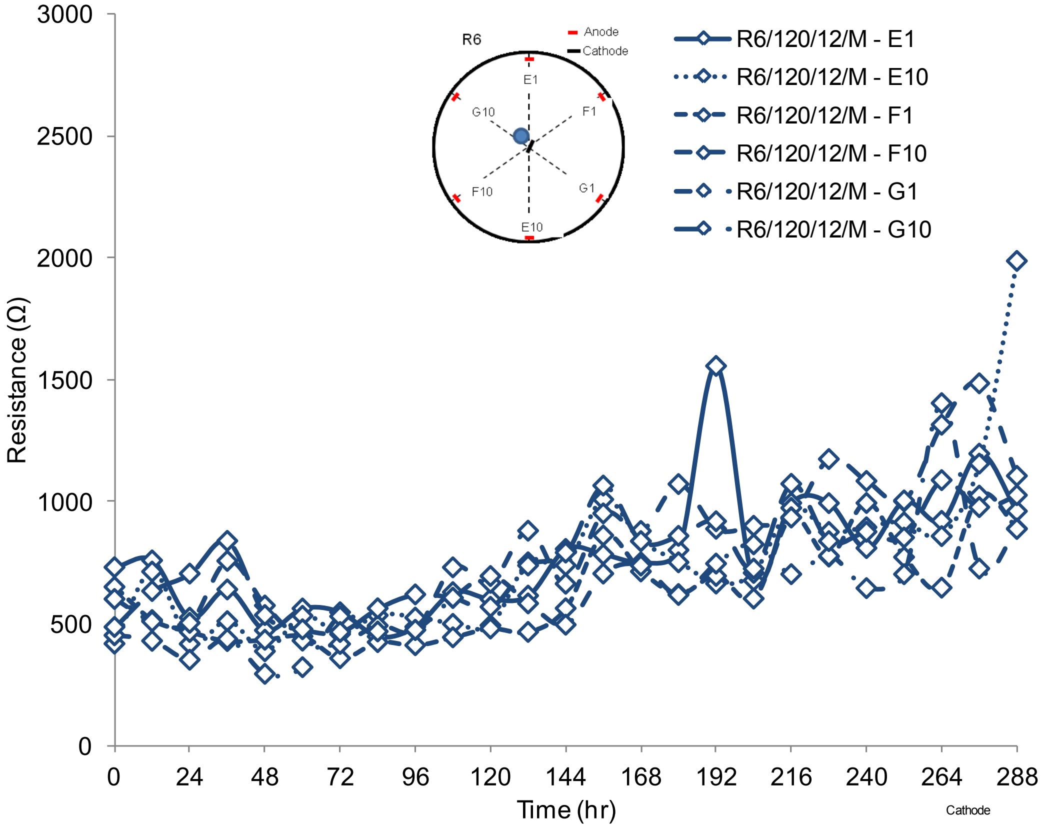
3000
2500
2000
1500
1000
500
0
Resistance (Ω)
R6
Anode
Cathode
E1
G10
F1
F10
G1
E10
R6/100/16/M - E1
R6/100/16/M - E10
R6/100/16/M - F1
R6/100/16/M - F10
R6/100/16/M - G1
R6/100/16/M - G10
0 24 48 72 96 120 144 168 192 216 240 264 288 312 336 360 384
Time (hr)
Cathode

(d)



3000
2500
2000
1500
1000
500
0
Resistance (Ω)
R4
Anode
Cathode
A1
D8
B1
C10
C1
B8
D1
A10
R4/120/12/M - A1
R4/120/12/M - A10
R4/120/12/M - C1
R4/120/12/M - C10
0 24 48 72 96 120 144 168 192 216 240 264 288
Time (hr)
Cathode

(e)



(f)

Figure 5.16: Variation in resistance at cathode region with time for (a) R4 and (b) R6 at 80V/m; (c) R4 and (d) R6 at 100V/m; and (e) R4 and (f) R6 at 120V/m

Figure 5.16(a) shows the resistance at the cathode region with time in the R4 test with voltage gradient of 80V/m. Initial resistance at the cathode region ranges from 437 to 768Ω. Unlike the overall resistance, a decreasing trend with time is observed in the resistance at the cathode region. Lowest resistance in the test is 151Ω at 132hr. After 132hr, the decreasing trend in resistance is less significant. At the end of the test, resistance at the cathode region range from 178 to 403Ω.

Figure 5.16(b) shows the variation in resistance with time at the cathode region in the R6 test with voltage gradient of 120V/m. Resistances at the cathode region for R6 show larger variation throughout the test duration. Initial resistance at the cathode region ranges from 366 to 591Ω. In comparison to initial resistances of the R4 test, the R6 test shows a lower range of initial resistances. The resistance near the cathode of the R6 test show increment in the first 24 hours. At 24hr, peak resistance of 861Ω is observed. Following that, there is a gradual reduction in resistance, with the exception of resistance near E1 which shows a high value of 761Ω. At 96hr, all recorded resistances drop to values between 187 to 341Ω. This sudden reduction in resistance corresponds to the higher current measured at the same time. After the sudden drop, all resistances increase again to values ranging from 302 to 706Ω. Another decline in resistance is seen at the end of the test with values ranging from 211 to 447Ω.

The decreasing trend in resistance at the cathode for both the R4 and R6 tests reflects the decreasing trend of voltage loss near the cathode. The reduction in resistance at the cathode might be due to EO flow toward the cathode. The movement of water toward the cathode increases conductivity of the area near the cathode. As the tests progressed, no significant increase in resistance at the cathode is observed in both the R4 and R6 tests.

Figure 5.16(c) presents the variation in resistance with time at the cathode region of the R4 test with voltage gradient of 100V/m. Initial resistance at the cathode region ranges between 583 to 702Ω. In the first 24 hours, significant reduction in resistance is observed. Between 24hr to 144hr, the resistances at the cathode region show lower values than the initial resistances. In this period of time the resistances range from 170 to 526Ω. Between 144hr and 252hr, fluctuation in resistance is less visible with a range from 330 to 448Ω. From 252hr onward, a gradual increase with time is observed. Peak resistance of 1244Ω is recorded at the end of the test. The peak in the resistance at the cathode region occurs at the same time as the overall resistance. Other resistance values at 384hr range from 671 to 830Ω.

Figure 5.16(d) presents the resistance with time at the cathode region in the R6 test with voltage gradient of 100V/m. Initial resistances at the cathode region range between 574 to 668Ω. This is similar to the initial resistance at the cathode region of the R4 test. A very gradual reduction with time in the resistance is observed until 96hr. Following that, the resistances start to exhibit an increasing trend with time until the end of the test at 384hr. A sudden peak in resistance occurred at 360hr with a magnitude of 2027Ω near E1. At the end of the test, resistances at the cathode region range from 854 to 1607Ω. The resistances of the cathode region in the R6 test show higher magnitudes at the later stage of the test compared to that of the R4 test. The peak in resistance at the cathode region of the R6 test also occurs at the same time as the peak in overall resistance.

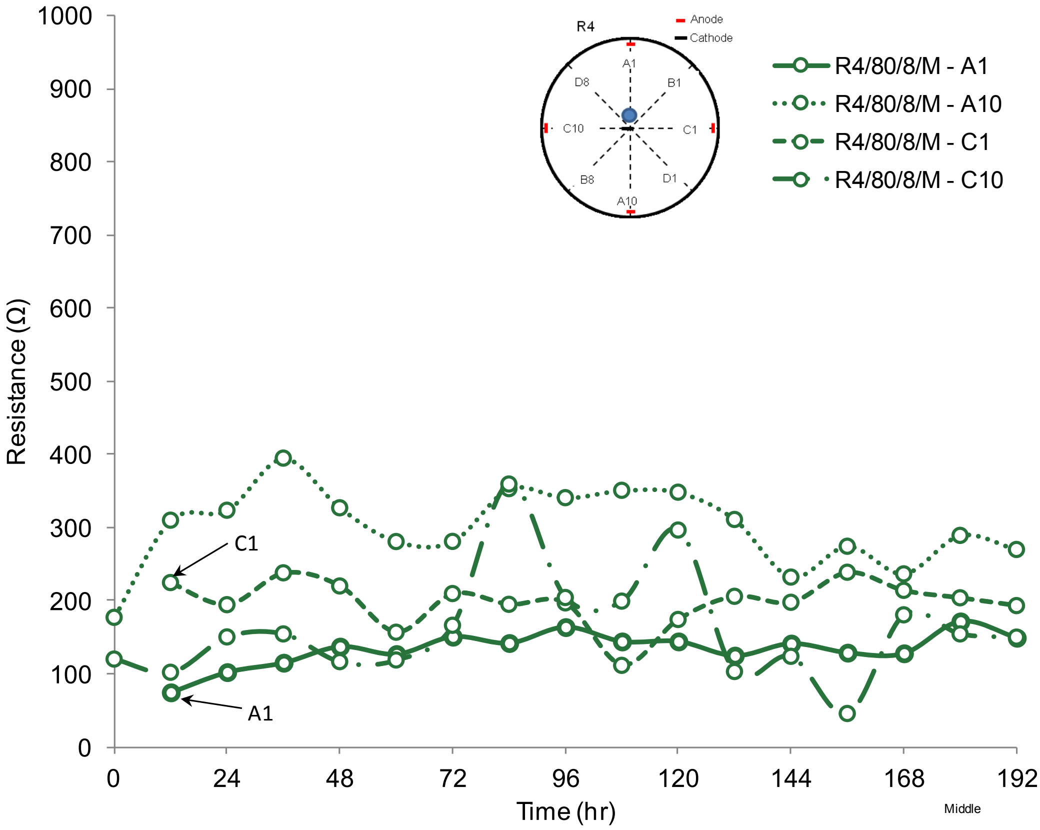
The reduction in resistance at the cathode region of the R4 and R6 electrode configuration tests with voltage gradient of 80V/m is also observed in the early stages of the tests with voltage gradient of 100V/m. This could be due to movement of water toward the cathode during EO, resulting in an increase in conductivity in the vicinity of the cathode. As the test progressed and water is removed from the peat, the volume of water moved to the cathode shows gradual decrease as observed in Section 5.3 earlier. With the decrease in EO flow toward the cathode, the conductivity also decreases. Coupled with the generation of hydrogen gas near the cathode, resistance at the cathode region shows increase. In the R6 test, the resistance shows a higher range, which might be due to higher generation of gas as a result of six anodes in the test configuration.

Figure 5.16(e) shows the resistance with time at the cathode region in the R4 test with voltage gradient of 120V/m. Initial resistance of the cathode region ranges from 401 to 499Ω. A slight reduction with time in the resistance is seen from the start of the test until 60hr. After 60hr, higher resistance is observed near A1 and A10 until the end of the test. Meanwhile, the resistances near C1 and C10 continue to show relatively lower resistance. At 180hr, the resistance near C1 starts to show increase with time until 204hr. At 204hr, the resistance near C1 is 708Ω. Increase of resistance near C10 is only observed at 228hr with a sharp increase to 646Ω. At the end of the test, the resistance at the cathode region ranges from 556 to 1465Ω, with the highest resistance near A1.

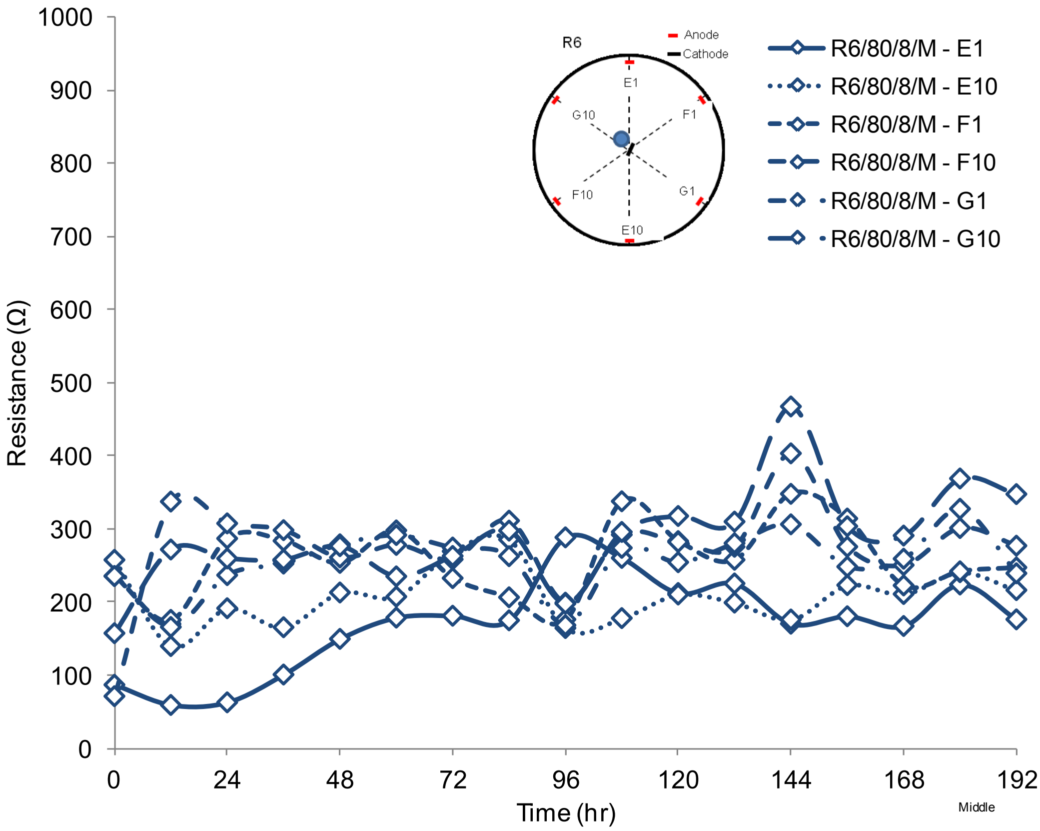
Figure 5.16(f) presents the resistance with time at the cathode region in the R6 test with voltage gradient of 120V/m. Initial resistance at the cathode region ranges from 417 to 730Ω. Fluctuations in the resistances are observed from the start of the test until 72hr. From 72hr onward, the resistance in the R6 test exhibit an increasing trend with time. By 192hr, the resistance has increased to range between 663 to 919Ω. At 192hr, the resistance near E1 shows a sudden peak with a magnitude of 1557Ω. By the end of the test, at 288hr, the resistance at the cathode region ranges from 887 to 1105Ω, while a high value of 1987Ω is recorded along E10.

As observed in the tests with voltage gradient of 80V/m and 100V/m, there is a slight decrease in resistance near the cathode of the R4 and R6 electrode configuration tests at the start of the EO test. With voltage gradient of 120V/m, the range of resistance near the cathode of the R4 test shows similarity to that of the R4 test with voltage gradient of 100V/m. For the R6 test with voltage gradient of 120V/m, a marginally higher range of resistance is observed at the later stage of the test compared to the R6 test with voltage gradient of 100V/m. At voltage gradient of 120V/m, the resistance near the cathode of the R6 test shows higher range than that of the R4 test. This is also observed in the resistance of the cathode region in R4 and R6 tests with voltage gradient of 100V/m. The higher resistance of the R6 test might be due to higher gas generated at the cathode with the configuration of six anodes.

5.5.3 Resistance at the middle region of the R4 and R6 EO tests

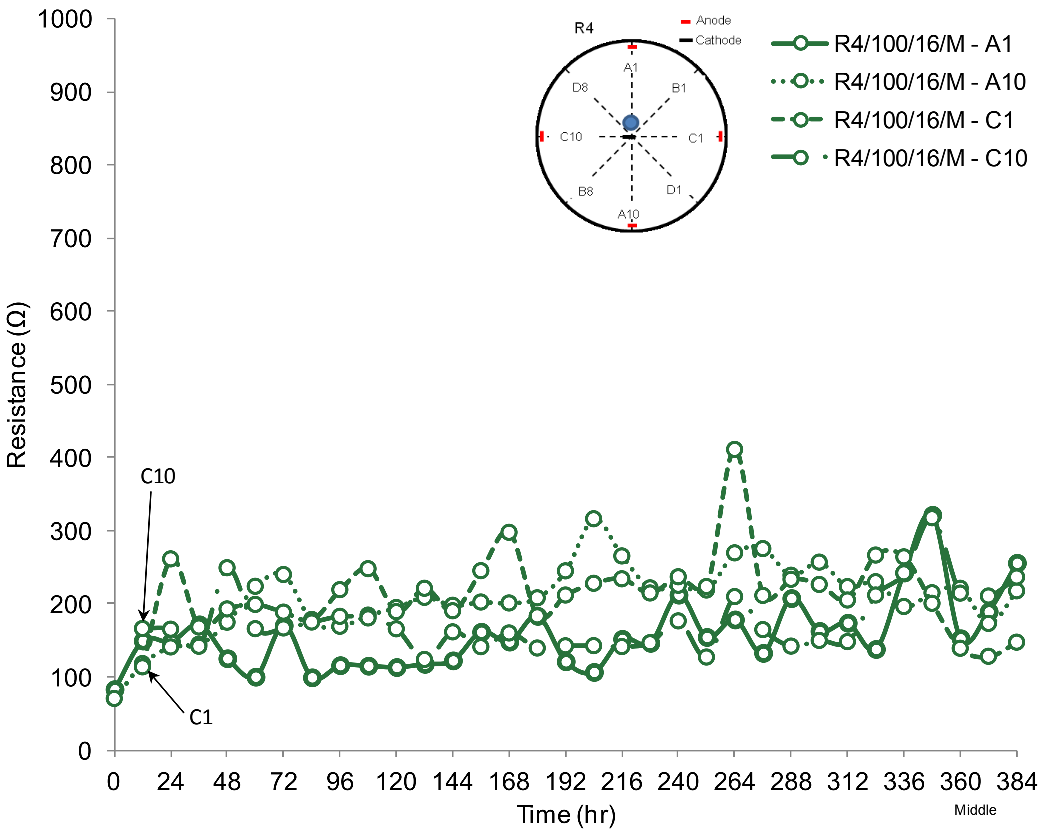


(a)



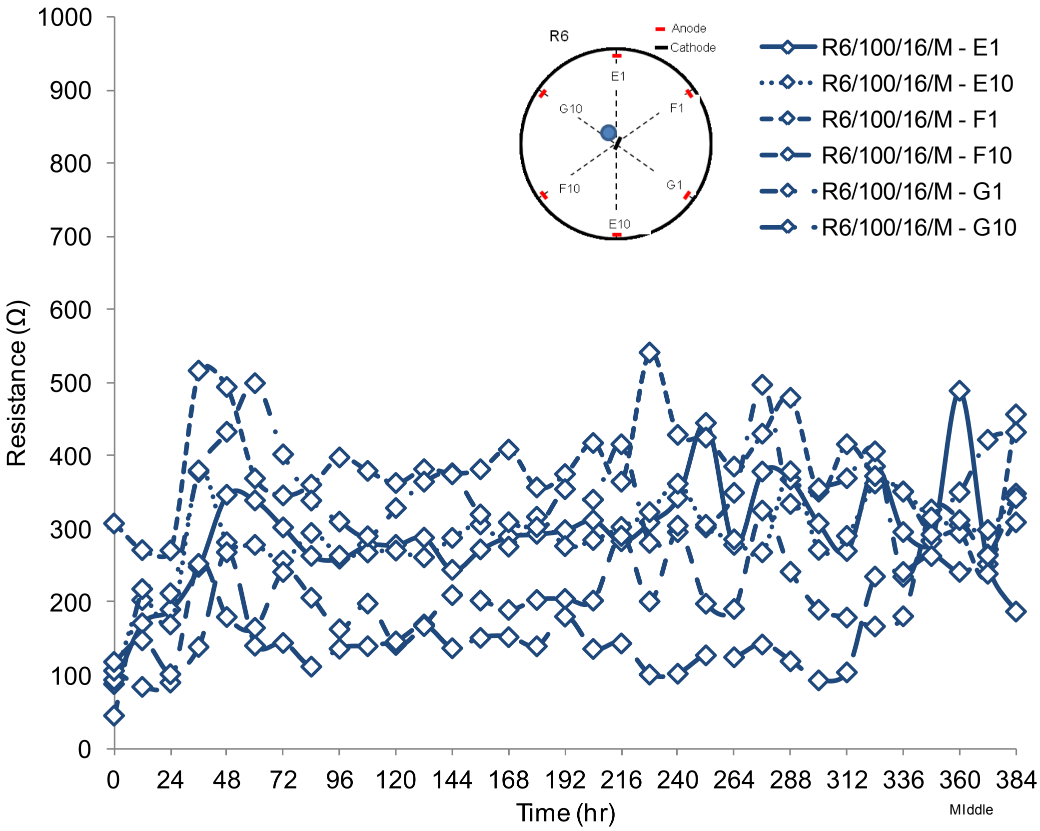
Resistance (Ω)
Time (hr)
Middle
R6
Anode
Cathode
E1
F1
G1
E10
F10
G10
R6/80/8/M - E1
R6/80/8/M - E10
R6/80/8/M - F1
R6/80/8/M - F10
R6/80/8/M - G1
R6/80/8/M - G10

(b)



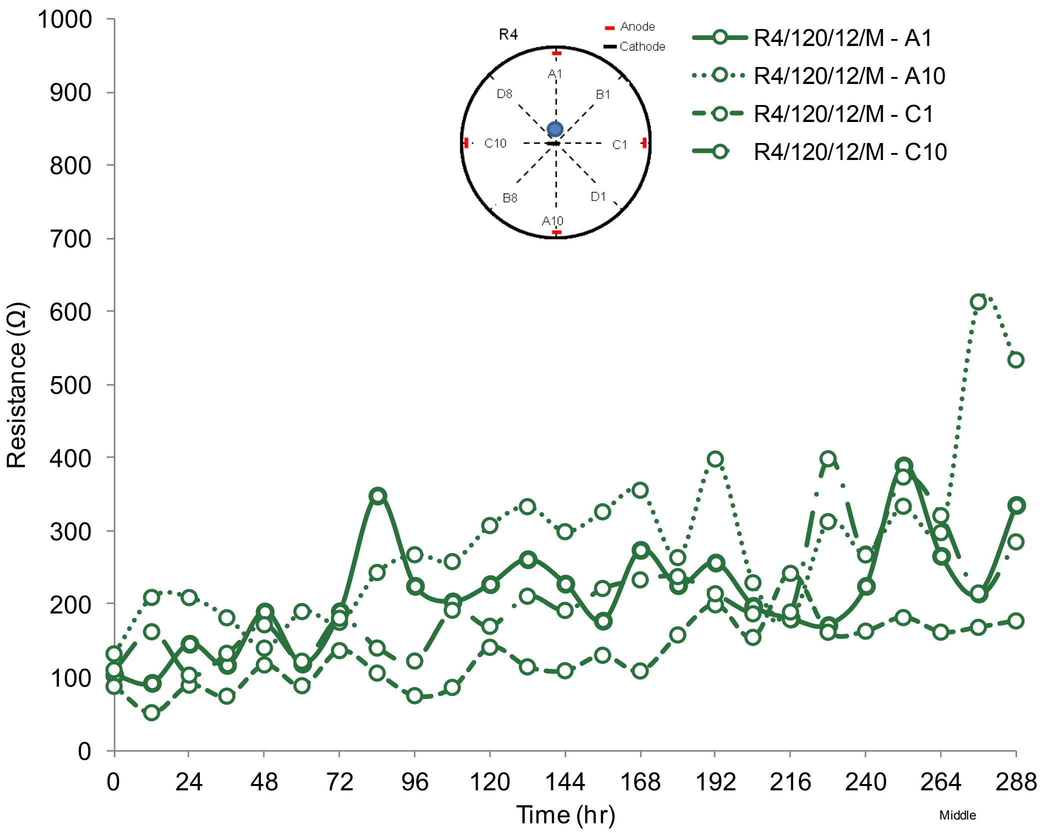
Resistance (Ω)
Time (hr)
Middle
R4
Anode
Cathode
A1
B1
C1
D1
A10
B8
C10
D8
R4/100/16/M - A1
R4/100/16/M - A10
R4/100/16/M - C1
R4/100/16/M - C10
C10
C1

(c)



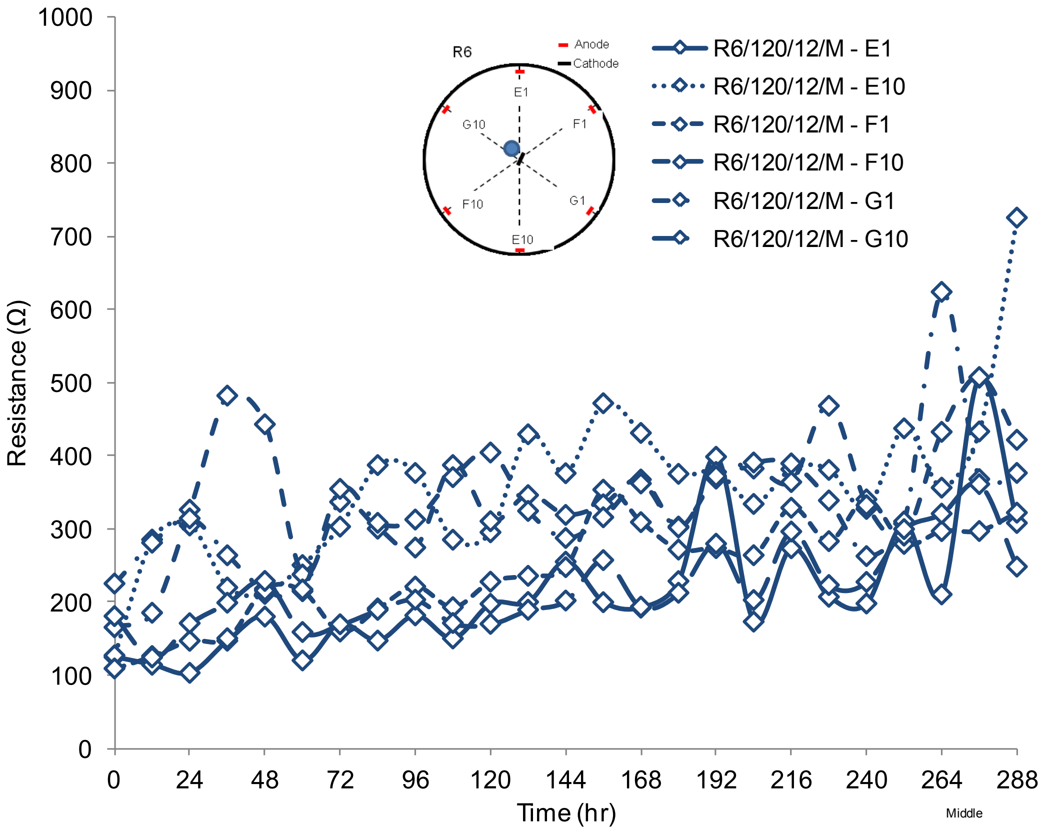
1000
900
800
700
600
500
400
300
200
100
0
Resistance (Ω)
0 24 48 72 96 120 144 168 192 216 240 264 288 312 336 360 384
Time (hr)
MIddle
R6
Anode
Cathode
E1
F1
G10
F10
G1
E10
R6/100/16/M - E1
R6/100/16/M - E10
R6/100/16/M - F1
R6/100/16/M - F10
R6/100/16/M - G1
R6/100/16/M - G10

(d)



1000
900
800
700
600
500
400
300
200
100
0
Resistance (Ω)
0 24 48 72 96 120 144 168 192 216 240 264 288
Time (hr)
Middle
R4
Anode
Cathode
A1
B1
D8
C10
C1
B8
D1
A10
R4/120/12/M - A1
R4/120/12/M - A10
R4/120/12/M - C1
R4/120/12/M - C10

(e)



(f)

Figure 5.17: Variation in resistance at middle region with time for (a) R4 and (b) R6 at 80V/m; (c) R4 and (d) R6 at 100V/m; and (e) R4 and (f) R6 at 120V/m

Figure 5.17(a) shows the resistance with time at the middle region in the R4 test with voltage gradient of 80V/m. The resistance of the middle region is obtained between the first and last voltage probes. Resistance of the middle region reflects the resistance of the peat during EO test. Initial resistance at the middle region is 120Ω and 177Ω near A10 and C10. For the other two anodes, A1 and C1, initial resistance could not be calculated due to large fluctuation in measured voltages through peat. At 12hr, resistance at the middle region range from 75 to 310Ω. The resistance of the middle region near A1 show a steady trend throughout the test with values ranging from 102 to 172Ω. The resistance at the middle region near A10 is the highest with peak resistance of 395Ω at 24hr. The resistance of the middle region near C1 mainly lies within the 200 to 250Ω range with noticeable fluctuation throughout the test. The resistance of the middle region near C10 exhibits the largest variation during the test duration. Resistance obtained is as low as 45Ω and as high as 359Ω.

Figure 5.17(b) shows the resistance with time at the middle region in the R6 test with voltage gradient of 80V/m. Initial resistance of the middle region range from 71 to 257Ω. The resistance near E1 shows the lowest overall resistance throughout the test. The other anodes recorded higher resistances in the range between 139 to 337Ω. At 96hr, all resistances show decrease except for the resistance near E1. The drop in resistance show values ranging from 168 to 198Ω. After that, the resistances increase again, with a maximum resistance of 467Ω at 144hr near G10. The resistance at the end of the test is between 176 to 347Ω.

No significant increasing or decreasing trend in the resistance is observed in the middle region of the R4 test. In the R6 test, a gradual increase of resistance with time is observed. The range of resistance at the middle region for R4 is from 45 to 359Ω and for R6 is from 71 to 467Ω. Comparing to the small scale test with 80V/m, the resistance of the middle region in the small scale test is higher at 348 to 654Ω. The range of resistance at the middle region for both R4 and R6 tests is lower compared to the cathode region of the same tests. In the field trial on sewage sludge by Glendinning *et al.* (2008), highest values of conductivity were recorded at the midpoints between electrodes. This coincides with the lowest range of resistance recorded at the middle region for both R4 and R6 tests.

Figure 5.17(c) shows the variation in resistance with time at the middle region of the R4 test with voltage gradient of 100V/m. Initial resistance at the middle region is 70Ω and 83Ω near A1 and A10 respectively. Initial resistance near C1 and C10 could not be ascertained due to fluctuations in voltage through peat. At 12hr, the resistances in peat increase to range from 114 and 166Ω. The resistance of the middle region near A1 shows an overall lower resistance among the four anodes. The highest resistance in the middle region for R4 occurs at 264hr with 411Ω near C1. Resistance of the middle region show a fluctuating trend throughout the test with values from as low as 99Ω to as high as 411Ω. At the end of the test, the resistance at the middle region range from 147 to 256Ω. A very gradual increasing trend with time can be observed in the resistance.

Figure 5.17(d) presents the resistance with time at the middle region in the R6 test with voltage gradient of 100V/m. The resistances of the middle region in the R6 test show larger variation compared to that of the R4 test. The initial resistance ranges from 44 to 118Ω, with a higher resistance of 307Ω near F1. Resistance throughout the test range from as low as 84Ω to as high as 541Ω. The lowest resistance is recorded along G10 at 12hr while the highest resistance is along F1 at 228hr. In spite of the fluctuating trend, no visible increasing or decreasing trend is observed in the resistance of the middle region. At the end of the test, the resistance range from 187 to 456Ω.

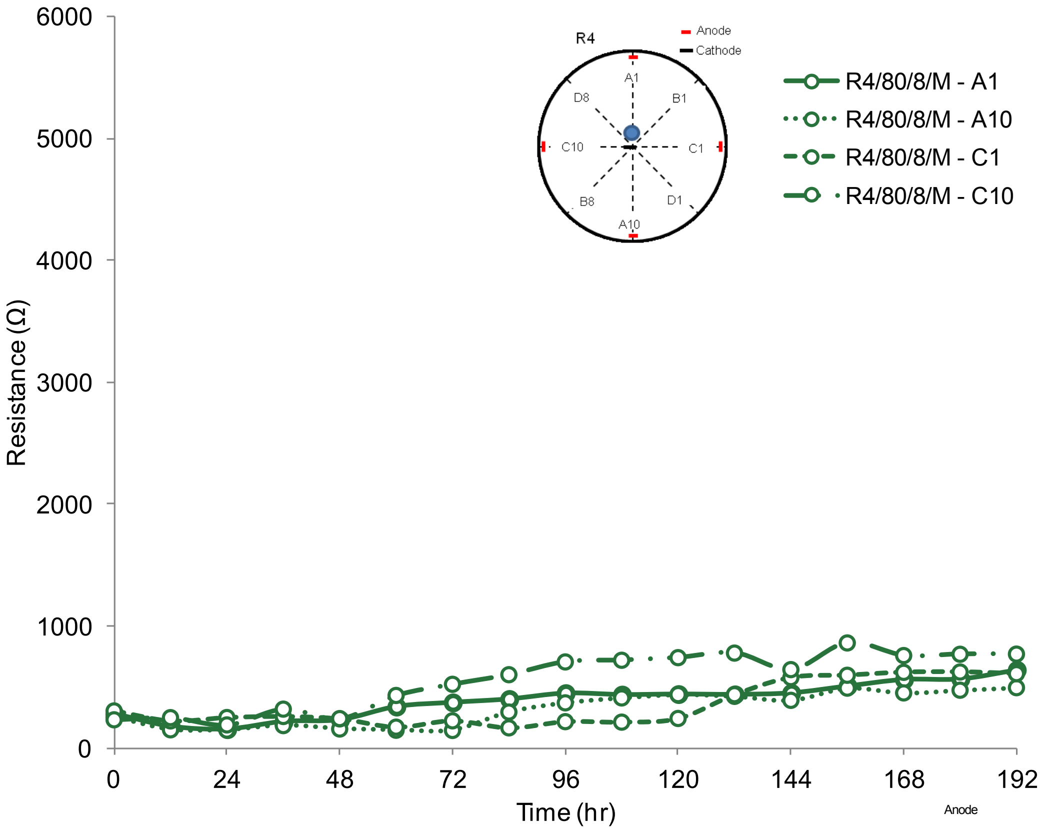
With voltage gradient of 100V/m, the range of resistances at the middle region of the R4 test is lower than that of the R6 test. This is reflected in the higher volume of water collected in the R4 test. The resistance of the middle region for both R4 and R6 electrode configuration is lower compared to the resistance of the cathode region of the same tests. Comparing to the resistance of the middle region in earlier tests with 80V/m, a similar range of resistance is observed. The resistance of peat did not show significant increase with the increase of voltage gradient to 100V/m.

Figure 5.17(e) shows the resistance with time at the middle region in R4 test with voltage gradient of 120V/m. The initial resistance at the middle region ranges from 87 to 132Ω. In spite of the fluctuating resistance at the middle region, a gradually increasing trend with time can be observed. Throughout the test, resistance at the middle region recorded values ranging from 51 to 390Ω. A sudden increase in resistance near A10 occurs at 276hr with 613Ω. Incidentally, it is also the highest resistance recorded in this test. At the end of the test, at 288hr, the resistance values are 177Ω, 285Ω, 336Ω and 534Ω.

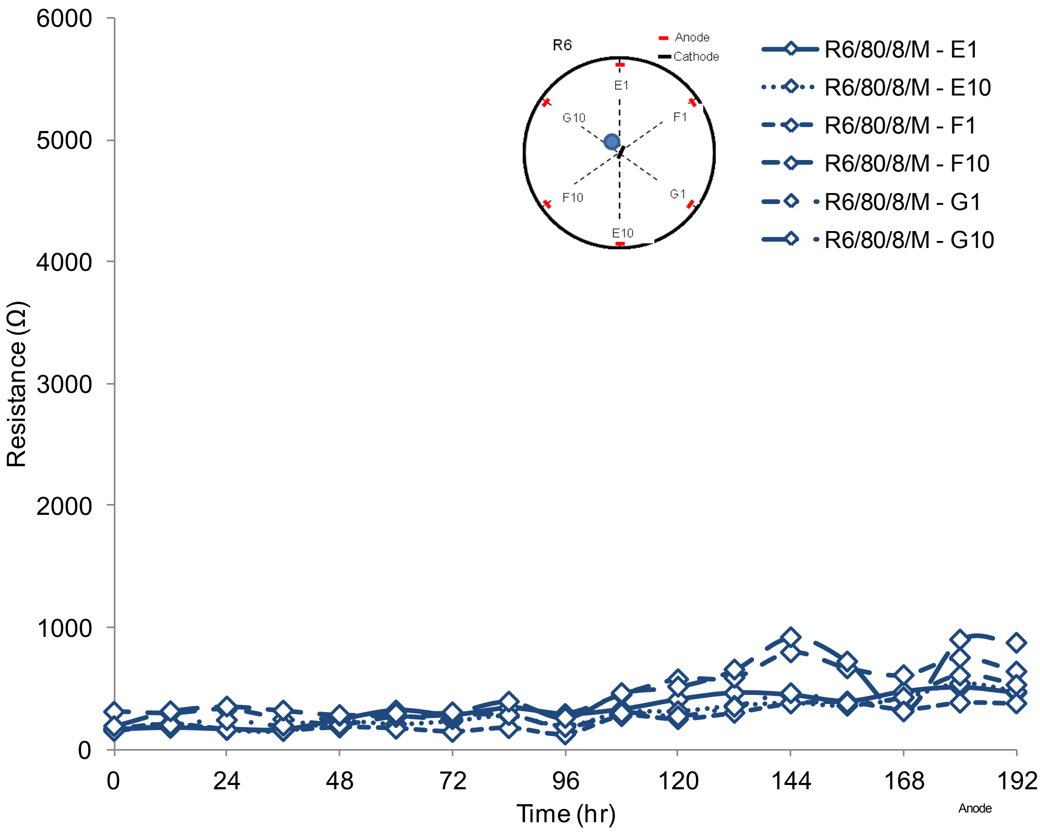
Figure 5.17(f) presents the resistance with time at the middle region in the R6 test with voltage gradient of 120V/m. The initial resistance ranges from 109 to 225Ω. The middle region resistance ranges from 104 to 470Ω for the test duration. An increasing trend in the resistance of the middle region can be observed. At the end of the test, the resistance ranges from 248 to 726Ω. The highest resistance of 726Ω is recorded along E10 at the end of the test.

At voltage gradient of 120V/m, the R6 test shows marginally higher range of resistance compared to that of the R4 test. The volume of water collected from both the tests also show marginal difference. The range of resistance at the middle region of the test peat the tests with voltage gradient of 120V/m show similarity to the series of tests with voltage gradients of 80V/m and 100V/m. The resistance at the middle region for 80V/m, 100V/m and 120V/m tests fall in the range from 50 to 500Ω. This shows that there is no significant increase in resistance of the peat when voltage gradient is increased.

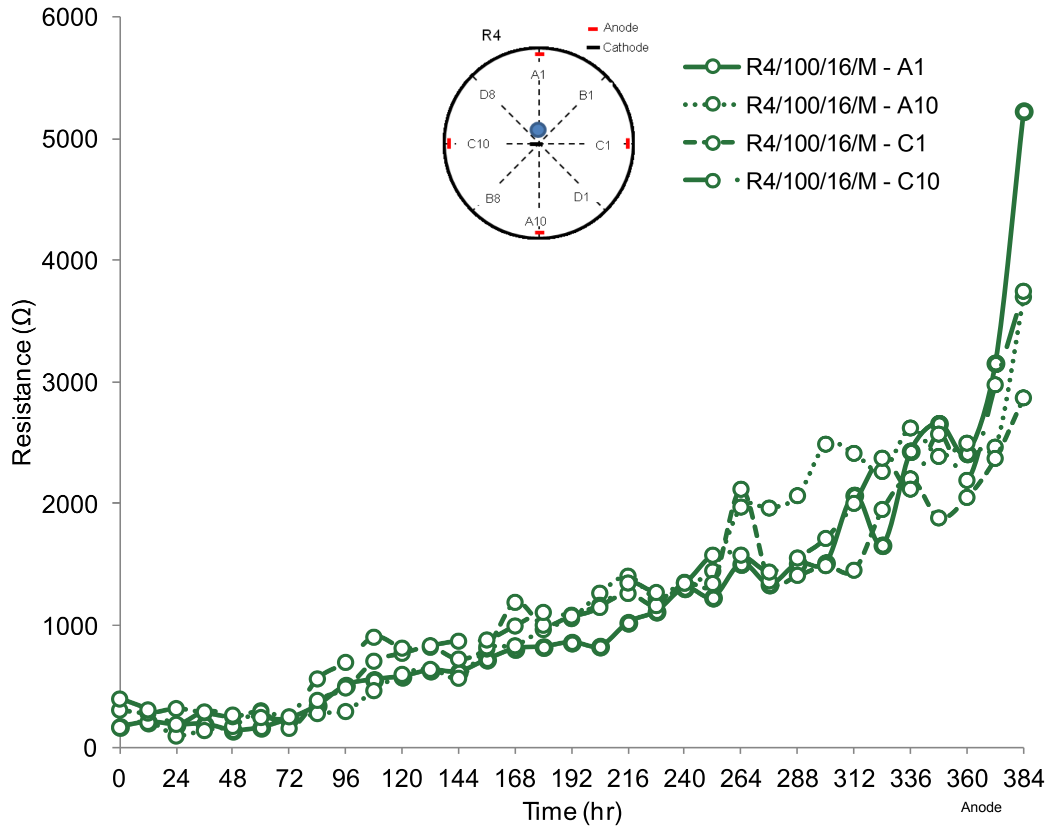
5.5.4 Resistance at the anode region of the R4 and R6 EO tests



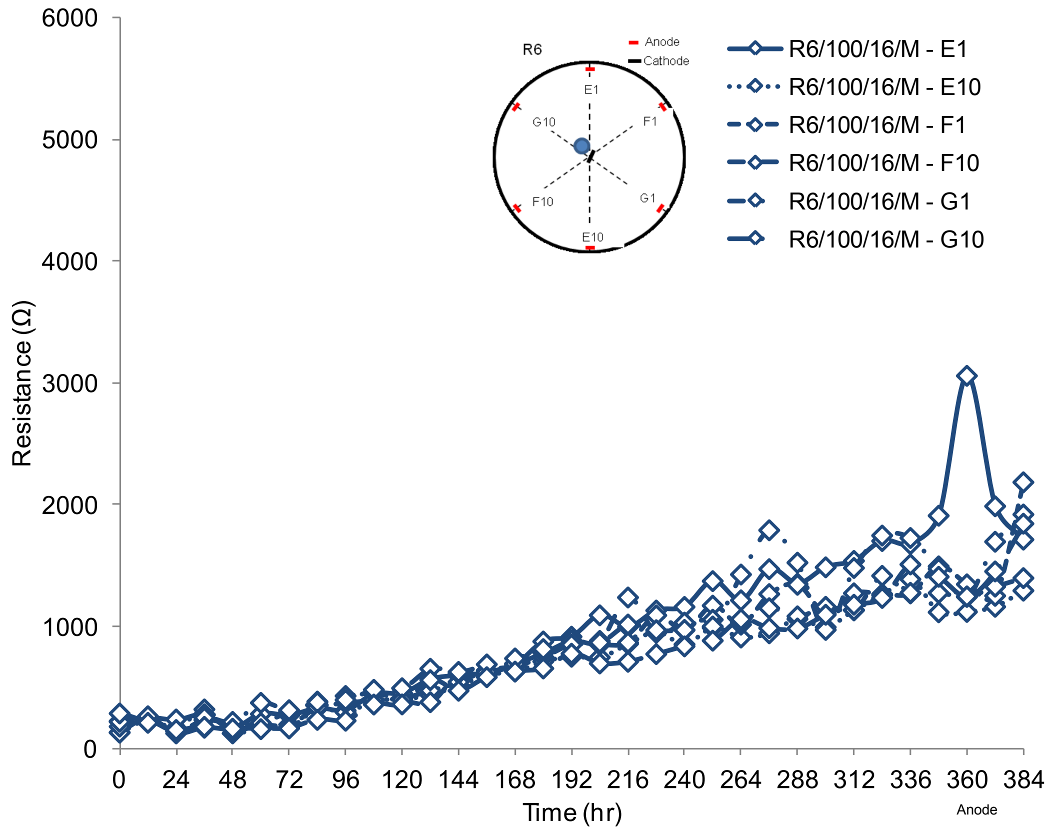
(a)



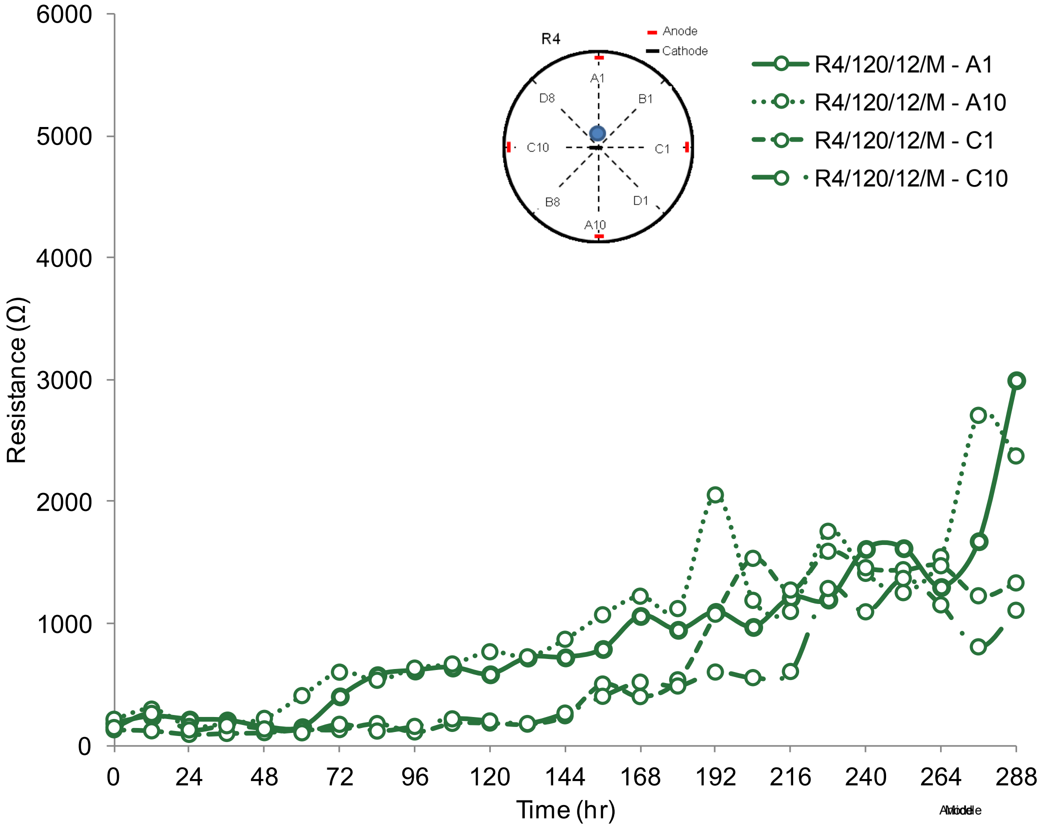
(b)


6000
5000
4000
3000
2000
1000
0
Resistance (Ω)
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
360
384
Time (hr)
Anode
R4
Anode
Cathode
A1
B1
C1
D1
A10
B8
C10
D8
R4/100/16/M - A1
R4/100/16/M - A10
R4/100/16/M - C1
R4/100/16/M - C10

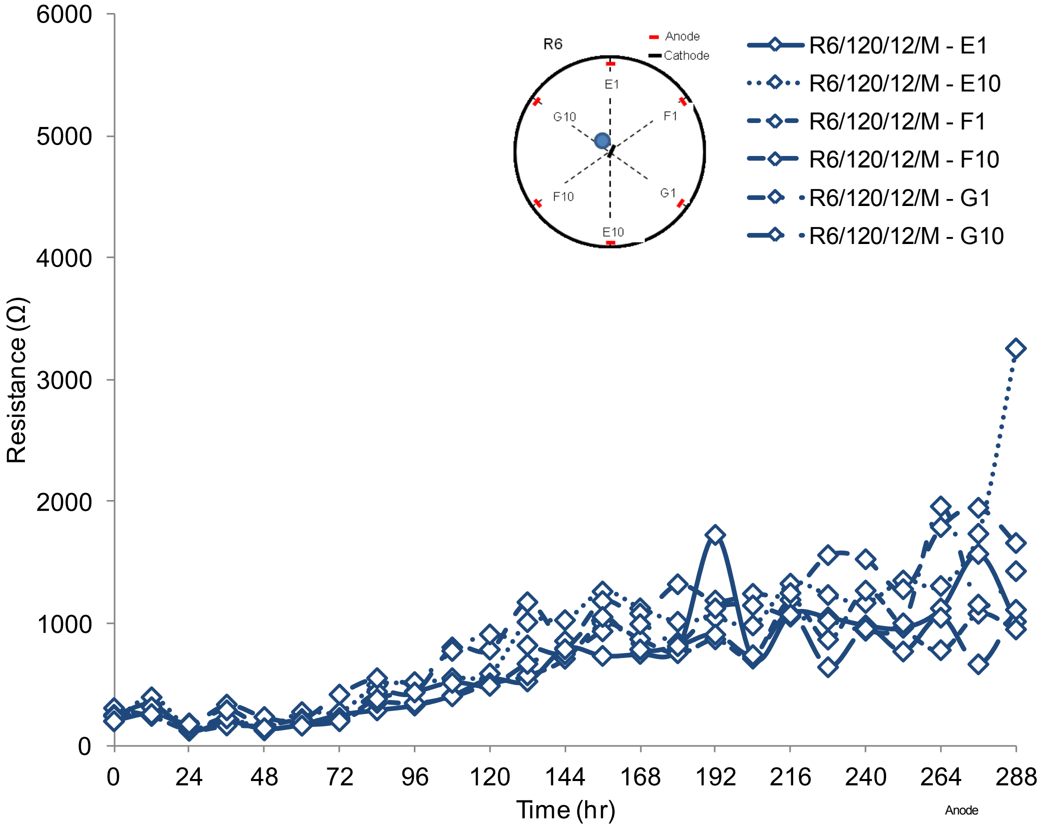
(c)


6000
5000
4000
3000
2000
1000
0
Resistance (Ω)
0
24
48
72
96
120
144
168
192
216
240
264
288
312
336
360
384
Time (hr)
Anode
R6
Anode
Cathode
E1
F1
G1
E10
F10
G10
R6/100/16/M - E1
R6/100/16/M - E10
R6/100/16/M - F1
R6/100/16/M - F10
R6/100/16/M - G1
R6/100/16/M - G10

(d)



(e)



(f)

Figure 5.18: Variation in resistance at anode region with time for (a) R4 and (b) R6 at 80V/m; (c) R4 and (d) R6 at 100V/m; and (e) R4 and (f) R6 at 120V/m

Figure 5.18(a) shows the variation in resistance at the anode region in the R4 test with voltage gradient of 80V/m. The resistance of the anode region is obtained between the anode and the last voltage probe at 0.91 normalized distance from the cathode. Initial resistances at the anode region range from 229 to 302Ω, which is lower than the range of initial resistance at the cathode region of the same test. The higher initial resistance at the cathode region might be attributed to the drainage well near the central cathode, resulting in reduced peat-electrode contact. From 48hr onward, the resistance at the anode region starts to exhibit gradual increase with time. The highest increment is near C10, with peak resistance of 860Ω at 156hr. At the end of the test, the resistances range from 493 to 768Ω.

Figure 5.18(b) shows the variation in resistance at the anode region of the R6 test with voltage gradient of 80V/m. At the start of the test, initial resistance at the canoed region range between 148 to 306Ω. The resistance remains fairly constant until 96hr with values ranging from 120 to 390Ω. From 96hr onward until the end of the test, the resistance shows an increasing trend. Largest variation is observed near G10 with peak resistance of 918Ω at 144hr, which then drops to 309Ω at 168hr before increasing again to 899Ω at 180hr. Resistance near F10 also shows significantly higher resistance in the range of 255 to 794Ω. At the end of the test, resistance in the anode region range from 375 to 873Ω.

Both the anode region for R4 and R6 electrode configuration tests show resistance increasing with time. The increase in resistance is also reflected in the increasing voltage losses near the anode. The resistance of the R4 test starts to show increment earlier at 48hr. The resistance of the R6 test only shows significant increase at 96hr, halfway through the test. This could be due to the lower EO flow in the R6 test and lower volume of water removed from the peat at the start of the test. As the water is moved away from the anode, reduction in moisture content near the anode increases resistance of the anode region. Oxygen gas generation at the anode could cause cavitation which leads to increase in resistance of the anode region as well. Increase in resistance could also be due to precipitation of hydroxides, changes in pH or a combination of these factors (Asadi *et al*. 2011a). Coincidentally, Glendinning *et al.* (2008) recorded lowest conductivity at the electrodes in their field trial on dewatering of sewage sludge.

Figure 5.18(c) presents the variation in resistance with time at the anode region in the R4 test with voltage gradient of 100V/m. Initial resistance at the anode region ranges from 201 to 393Ω. A slight reduction in all resistances is observed until 72hr. At 72hr of the test, the resistance at the anode region range from 152 to 241Ω. From 72hr onward, all resistances show an increasing trend with time until the end of the test at 384hr. By 192hr, the resistance has increased to range from 859 to 1076Ω. At the end of the test, the resistance recorded are 2870Ω, 3700Ω, 3747Ω and 5230Ω. Peak resistance at the anode region is recorded near A1. The peaks in resistance near the cathode and anode is reflected in the peak in overall resistance.

Figure 5.18(d) shows the variation in resistance with time at the anode region in the R6 test with voltage gradient of 100V/m. Initial resistance ranges from 175 to 283Ω. From 72hr onward, the resistances start to exhibit gradual increment with time. By 192hr, the resistance has increased to range from 774 to 882Ω. The resistances at the anode region continue to increase until the end of the test. At 360hr, a peak resistance of 3058Ω is recorded along E1. A peak is also observed near E1 in the resistance at the cathode region. The combination of the peaks in resistance at the cathode and anode region near E1 is observed as the maximum in the overall resistance. At the end of the test, resistance values range from 1293 to 2183Ω.

As observed earlier in the tests with voltage gradient of 80V/m, the initial resistances near the anode of the tests with voltage gradient of 100V/m are lower than the initial resistances near the cathode of the same tests. An increasing trend in resistance with time can be observed from both the R4 and R6 test. The increase in resistance at the anode region of the R6 test shows lower magnitudes compared to the R4 test. The resistance of the anode region is relatively higher compared to the resistance of the cathode region in this set of test. This could be due to the higher reduction in moisture content in the vicinity of the anode compared to the cathode. Gas generation at the anode could also increase resistance near the anode.

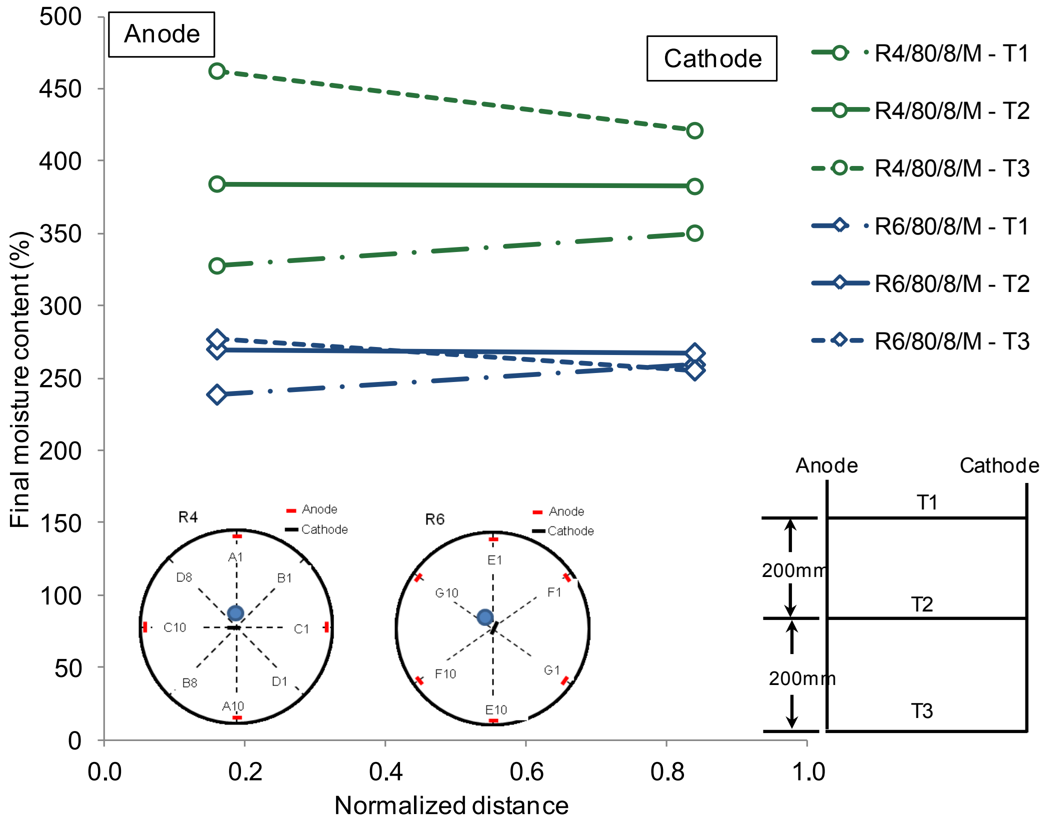
Figure 5.18(e) presents the resistance with time at the anode region in the R4 test with voltage gradient of 120V/m. Initial resistance at the anode region at the start of the test ranges from 126 to 212Ω. The resistance starts to show increment with time from 48hr onward. Earliest increase in resistance is seen near A10 at 60hr followed by resistance near A1 showing increase at 72hr. Resistances along C1 and C10 remain at a lower magnitude until 108hr where a slight increase is observed. Larger increase in resistance along C1 and C10 can be seen from 156hr onward until the end of the test. By 192hr of the test, resistance at the anode region ranges from 600 to 2054Ω. At the end of the test, resistance along A1 and A10 recorded significantly higher magnitudes at 2998Ω and 2374Ω respectively. At 288hr, resistance along C1 and C10 are 1332Ω and 1107Ω respectively.

Figure 5.18(f) shows the variation in resistance with time at the anode region in the R6 test with voltage gradient of 120V/m. Initial resistance of the anode region ranges from 196 to 303Ω. From 72hr onward, the resistance at the anode region starts to exhibit gradual increment with time. At 72hr, the resistances range from 195 to 415Ω. By 192hr, the resistance has increased to range from 907 to 1726Ω. At the end of the test, resistance ranges from 950 to 1659Ω, with highest resistance of 3257Ω along E10. Resistance near the anode of the R6 test shows higher magnitudes at the later stage of the test compared to that of the R4 test.

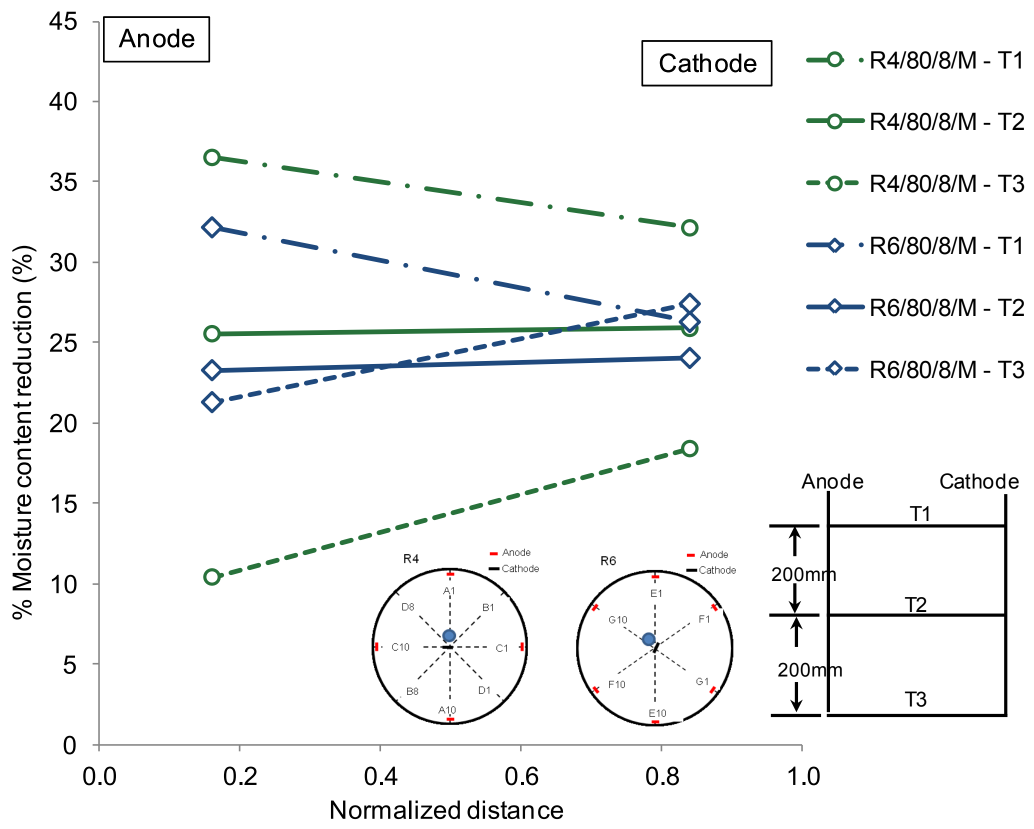
In the R4 and R6 electrode configuration tests with voltage gradient of 120V/m, the resistance of the anode region show similar ranges, with marginally higher range of resistance in the R6 test. The resistance of the anode region in the tests with voltage gradient of 120V/m is higher than that of the cathode and middle region of the same test. This could be due to the movement of water away from the cathode and reduction in moisture content in the vicinity of the anode. Generation of oxygen gas due to electrolysis at the anode could also lead to increase in resistance.

5.6 Moisture content post R4 and R6 EO tests

5.6.1 Moisture content of peat in R4 and R6 EO tests with voltage gradient of 80V/m



(a)



(b)

Figure 5.19: (a) Final moisture content; (b) Percentage of moisture content reduction at surface, mid-depth and bottom of peat after EO tests with R4 and R6 electrode configuration with voltage gradient of 80V/m

Figure 5.19(a) shows the final moisture content of peat along A1-A5 of the R4 test and E1-E5 of the R6 tests after EO with voltage gradient of 80V/m. The rest of the final moisture content data collected from the R4 and R6 tests are included as Appendix A 23 to A 25. Appendix A 23 shows the final moisture contents at peat surface for R4 and R6 tests. Appendix A 24 shows the final moisture contents at mid-depth of approximately 200mm below peat surface. Appendix A 25 shows the final moisture contents at the bottom of the peat for R4 and R6 tests.

For the R4 test, initial moisture content was 516%. Along A1-A5, final moisture content near the anode is 327%, 384% and 462% at top (T1), middle (T2) and bottom (T3) respectively. Near the cathode, final moisture content is 350%, 382% and 421% at T1, T2 and T3 respectively. For the other anodes along A and C, the final moisture content near the anode ranges from 313 to 419% while final moisture content near the cathode ranges from 354 to 473%. The final moisture contents are lowest at the peat surface and highest at the bottom of the peat. The final moisture contents near the anode are lower than the final moisture contents near the cathode. This could be attributed to the EO flow from the anode to the cathode. In the R4 test, Grids B and D denote the area without anodes. Peat samples were collected near the test tank wall and the central drainage well. Final moisture content ranges from 344 to 459% and 346 to 469% near the test tank wall and central drainage well respectively. The trend of lower final moisture content at the peat surface and higher final moisture content at the bottom of peat is also seen in the areas without electrodes. The final moisture contents near the test tank wall are lower than the final moisture contents near the central drainage wall.

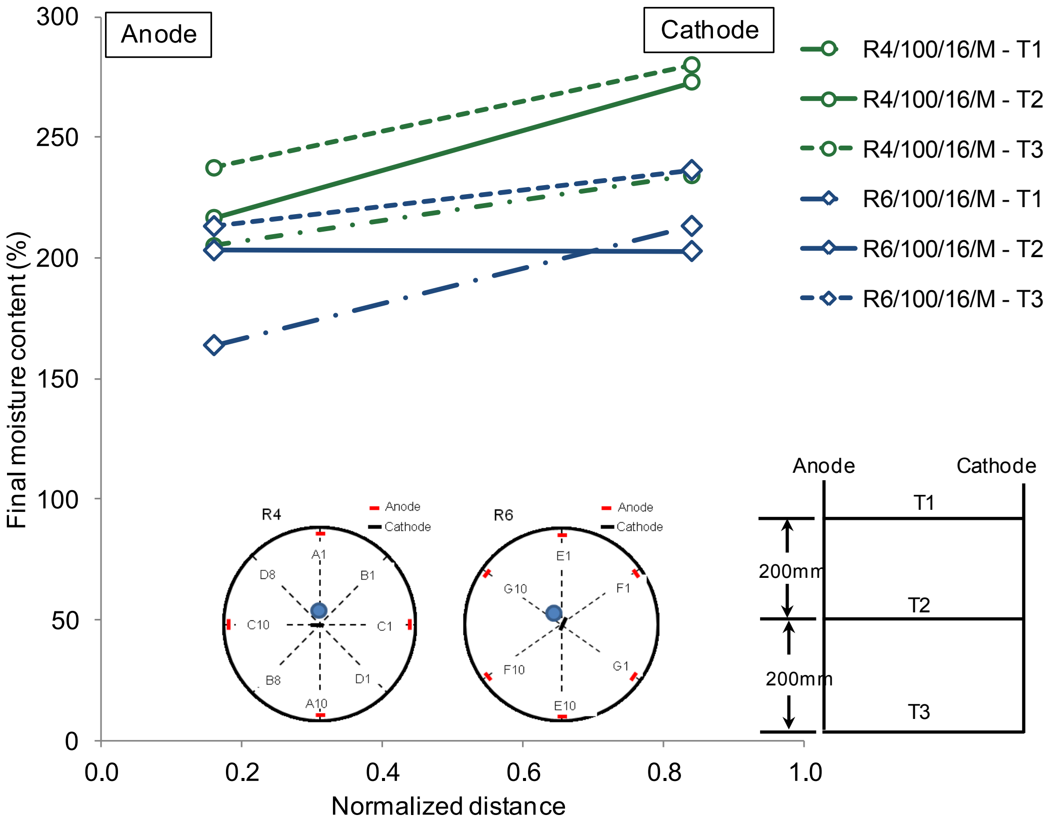
For the R6 test, initial moisture content was 351%. Along E1-E5, final moisture content near the anode is 238 to 276% at T1, T2 and T3 respectively. Final moisture content near the cathode is 255 to 267% at T1, T2 and T3 respectively. For the other anodes of the R6 test, final moisture content ranges from 219 to 294% and 249 to 274% near the anode and cathode respectively. No noticeable trend is observed in the final moisture content of the R6 test.

Figure 5.19(b) shows the percentage of moisture content reduction along A1-A5 of the R4 test and E1-E5 of the R6 test. Percentage of moisture content reduction is calculated as the percentage of change in moisture content over the initial moisture content. Appendix A 26 to A 28 shows the percentage of moisture content reduction for all other grids in the R4 and R6 tests at peat surface, mid-depth and bottom of the peat respectively.

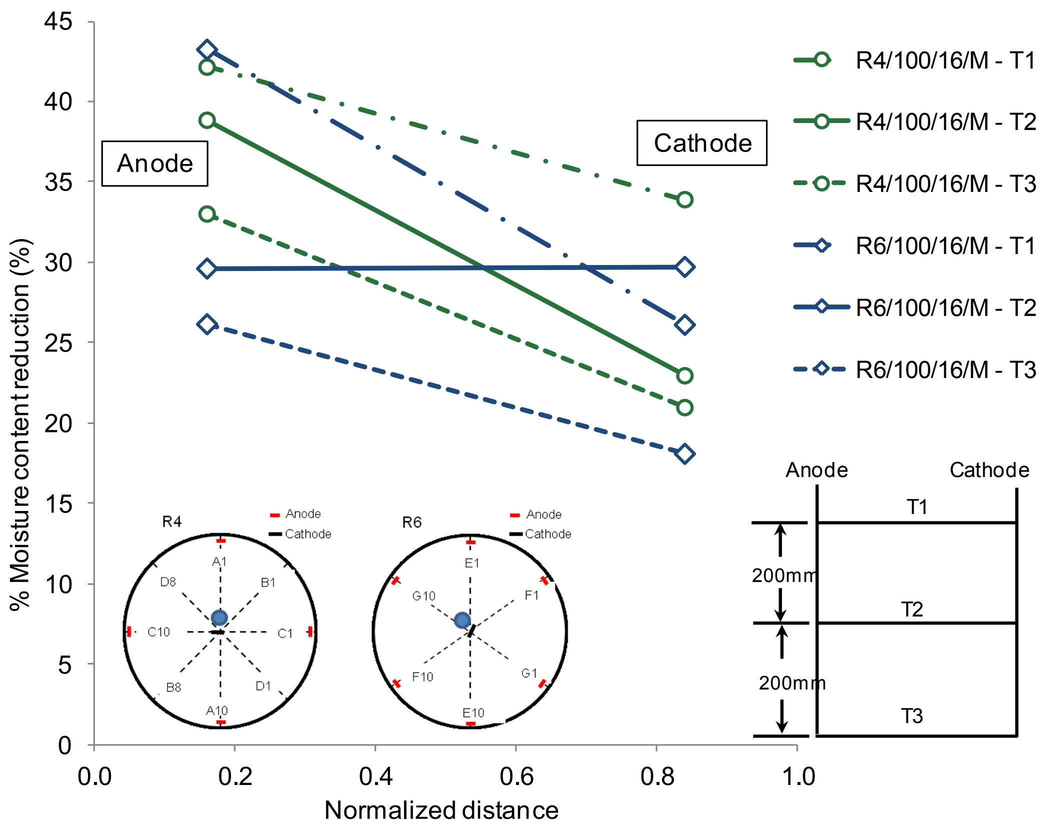
The R4 electrode configuration test shows moisture content reduction ranging from 10 to 36% and 18 to 32% near the anode and cathode respectively. Lowest moisture content reduction is 10% at the bottom of the peat. At the end of the test, the bottom of the test peat for R4 test was found to be visibly wet. For the other anodes of the R4 test, moisture content reduction ranges from 19 to 39% and 8 to 33% near the anode and cathode respectively. Moisture content reduction decreases with depth. Areas near the anodes underwent higher moisture content reduction compared to the areas near the cathode. Along Grids B and D, the area without anodes, the moisture content reduction ranges from 11 to 33% and 9 to 33% near the test tank wall and central cathode respectively. The area between anodes show relatively lower moisture content reduction compared to the area near the anodes. Higher moisture content reduction is observed at the peat surface and lower moisture content reduction is observed at the bottom of the peat.

For the R6 electrode configuration test, the final moisture content reduction ranges from 21 to 32% and 24 to 27% near the anode and cathode respectively. For the other anodes of the R6 test, moisture content reduction near the anode ranges from 16 to 38%. Near the cathode, moisture content reduction ranges from 22 to 30%. Decreasing moisture content reduction with depth is also observed in the R6 test. The decrease in moisture content reduction of the R6 test is lower than that of the R4 test. Moisture content reduction of the R6 test shows lower variation between the areas near the anode and cathode.

5.6.2 Moisture content of peat in EO tests with voltage gradient of 100V/m



(a)



(b)

Figure 5.20: (a) Final moisture content; (b) Percentage of moisture content reduction at surface, mid-depth and bottom of peat after EO test with R4 and R6 electrode configuration with voltage gradient of 100V/m

Figure 5.20(a) shows the final moisture content of peat along A1-A5 of the R4 test and E1-E5 of the R6 test after EO tests with voltage gradient of 100V/m. The rest of the final moisture content data collected from the R4 and R6 tests are included as Appendix A 43 to A 45.

For the test with R4 electrode configuration, initial moisture content was 354%. Final moisture content along A1-A5 ranges from 205 to 237% and 234 to 280% near the anode and cathode respectively. Lower final moisture content is at peat surface, T1 and higher final moisture content is at the bottom, T3.For sections along the other anodes, final moisture content ranges from 218 to 252% and 241 to 303% near the anode and cathode respectively. The final moisture contents are lowest at the peat surface and highest at the bottom of the peat. The final moisture contents near the anode are lower than that near the cathode. These trends are similar to the R4 test with 80V/m. For the areas without electrodes of the R4 test (Grids B and D), final moisture content ranges from 213 to 279% and 241 to 305% near the test tank wall and central drainage well respectively. No visible trend can be observed in the final moisture content of the areas between the anodes.

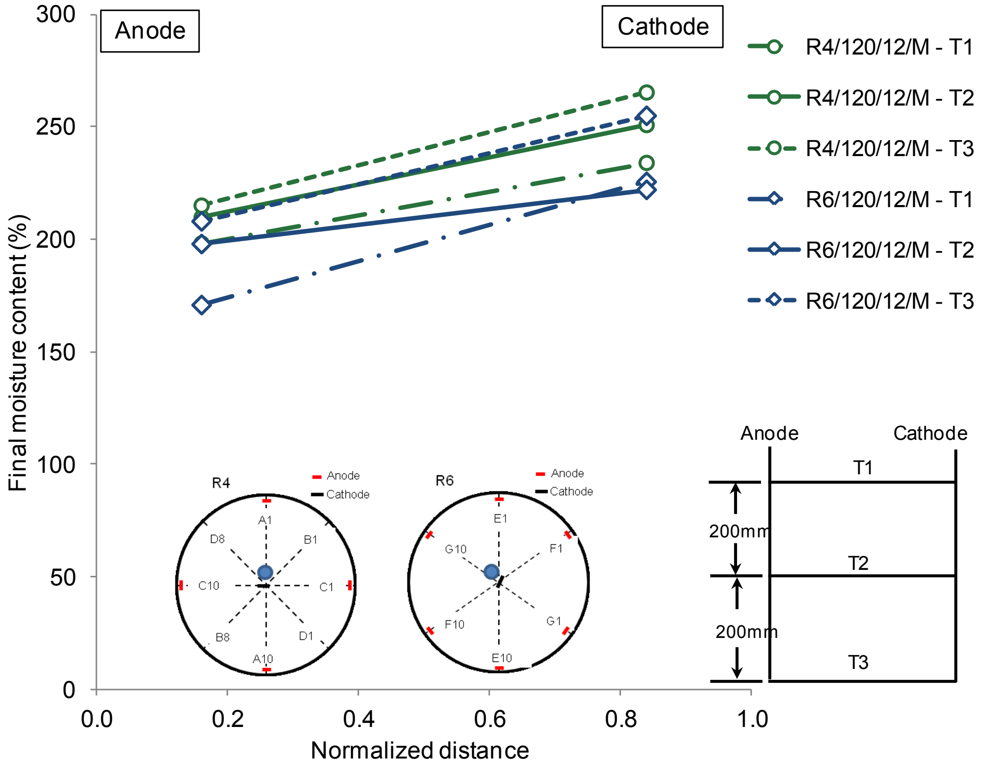
For the R6 electrode configuration test, initial moisture content was 288%. Final moisture content ranges from 164 to 213% and 203 to 236% near the anode and cathode respectively. Along E1-E5, final moisture content ranges from 139 to 214% and 172 to 265% near the anode and cathode respectively. The final moisture content is lower at the peat surface and higher at the bottom of the peat. At the same time, the final moisture content is lower near the anode and higher near the cathode.

Figure 5.20(b) presents the percentage of moisture content reduction along A1-A5 of the R4 test and E1-E5 of the R6 test. Appendix A 46 to A 48 show the percentage of moisture content reduction for all other grids in the R4 and R6 tests at peat surface (T1), mid-depth (T2) and bottom (T3) of the peat respectively.

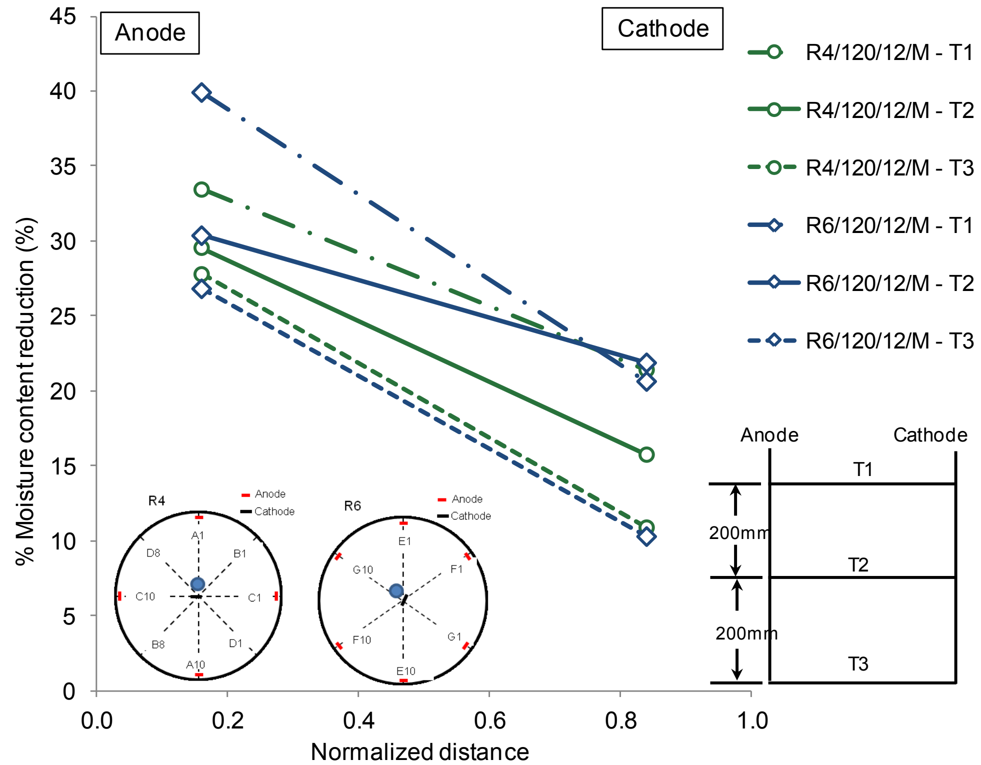
Along A1-A5 of the R4 test, moisture content reduction near the anode is 42%, 39% and 33% at T1, T2 and T3 respectively. Near the cathode, moisture content reduction is 34%, 23% and 21% at T1, T2 and T3 respectively. For the other anodes in the R4 test, the moisture content reduction ranges from 29 to 39% and 14 to 32% near the anode and cathode respectively. Moisture content reduction decreases with depth. Areas near the anode underwent higher moisture content reduction compared to the areas near the cathode. For the area between anodes, along Grids B and D, moisture content reduction ranges from 21 to 40% and 14 to 31% near the test tank wall and drainage well respectively. The areas between anodes do not show the decreasing trend in moisture content with depth.

Along E1-E5 of the R6 test, moisture content reduction ranges from 21 to 43% and 18 to 30% near the anode and cathode respectively. For the other anodes in the R6 test, moisture content reduction ranges from 30 to 52% and 8 to 36% near the anode and cathode respectively. Decreasing moisture content reduction with depth is also observed in the R6 test. However, the moisture content reduction near the anode at T2 is lower than that of the other five anodes in the R6 test. This might be due to some loss of contact between the anode and peat at that area. With the possible loss of contact, lower current would be transmitted, hence resulting in lower moisture content reduction. The overall higher moisture content reduction of the R6 test reflects the higher volume of water collected and higher settlement of the test.

5.6.3 Moisture content of peat in EO tests with voltage gradient of 120V/m



(a)



(b)

Figure 5.21: (a) Final moisture content; (b) Percentage of moisture content reduction at surface, mid-depth and bottom of peat after EO tests with R4 and R6 electrode configuration at 120V/m

Figure 5.21(a) shows the final moisture content of peat along A1-A5 of the R4 test and E1-E5 of the R6 test after EO tests with voltage gradient of 120V/m. The rest of the final moisture content data collected from the R4 and R6 tests are included as Appendix A 63 to A 65.

For the R4 electrode configuration test, initial moisture content was 297%. Final moisture content along A1-A5 ranges from 198 to 215% and 234 to 265% near the anode and cathode respectively. For the other sections with anodes (Grids A and C), the final moisture content ranges from 146 to 263% and 213 to 296% near the anode and cathode respectively. The final moisture content is lowest at the peat surface (T1) and highest at the bottom (T3) of the peat. Final moisture content near the anode is lower than that near the cathode. This is similar to the trend observed in R4 tests with voltage gradient of 80V/m and 100V/m. For the area without anodes (Grids B and D), final moisture content ranges from 195 to 293% and 209 to 279% near the test tank wall and drainage well. In the area between anodes, the final moisture content is lowest at the peat surface and increases with depth. The area near the test tank wall show relatively lower range of moisture content compared to the area near the central drainage well.

For the R6 electrode configuration test, initial moisture content was 284%. Along E1-E5, final moisture content ranges from 171 to 208% and 222 to 255% near the anode and cathode respectively. For the other anodes along Grids E, F and G, final moisture content ranges from 162 to 225% and 209 to 240% near the anode and cathode respectively. Final moisture content is lower at the surface (T1) and lower at the bottom (T3). Final moisture content is also lower near the anode and higher near the cathode. This trend in final moisture content of the R6 test is also observed in tests with voltage gradient of 80V/m and 100V/m.

Figure 5.21(b) presents the percentage of moisture content reduction along A1-A5 of the R4 test and E1-E5 of the R6 test. Appendix A 66 to A 68 show the percentage of moisture content reduction for all other grids in the R4 and R6 tests at peat surface (T1), mid-depth (T2) and bottom (T3) of the peat respectively.

In the R4 test, moisture content reduction along A1-A5 ranges from 28 to 33% and 11 to 21% near the anode and cathode respectively. At the other anodes of the R4 test, the moisture content reduction ranges from 11 to 46% and 0.6 to 33% near the anode and cathode respectively. Moisture content reduction decreases with depth. Areas near the anodes underwent higher moisture content reduction compared to the areas near the cathode. At the end of the test, the peat near the central cathode and drainage well was still considerably wet at several locations. For the areas without anodes (Grids B and D), moisture content reduction ranges from 1.5 to 36% and 6 to 30% near the test tank wall and central drainage well respectively. The moisture content reduction along Grids B and D also shows a trend of decreasing moisture content reduction with depth.

For the R6 electrode configuration test, moisture content reduction along E1-E5 ranges from 27 to 40% and 10 to 22% near the anode and cathode respectively. For the other anodes of the R6 test, moisture content reduction ranges from 20 to 43% and 15 to 26% near the anode and cathode respectively. Decreasing moisture content reduction with depth is also observed in the R6 test. In the R6 test, the moisture content reduction show lower variation compared to that of the R4 test (Appendix A 63 to A 65).

5.7 Shear strength post R4 and R6 EO tests

5.7.1 Undrained shear strength of peat at voltage gradient of 80V/m

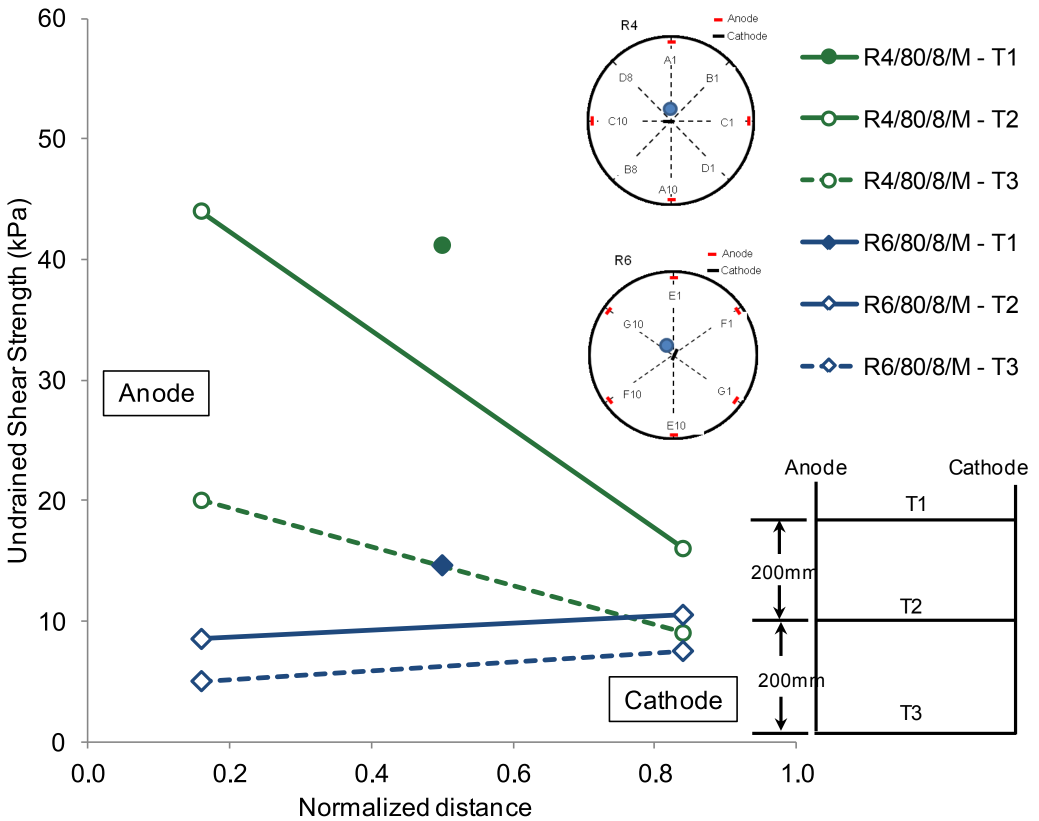


Figure 5.22: Final undrained shear strength of peat in EO tests with R4 and R6 electrode configurations at voltage gradient of 80V/m

Figure 5.22 shows the final undrained shear strength at the surface (T1), mid-depth (T2) and bottom (T3) of the peat along A1-A5 of the R4 test and E1-E5 of the R6 test. Figure 5.22(a) shows the final undrained shear strength for the R4 and R6 tests with voltage gradient of 80V/m. Appendix A 29 shows all the data for final undrained shear strength for test with R4 electrode configuration. Appendix A 30 presents all the data for final undrained shear strength for test with R6 electrode configuration. Both tests with R4 and R6 electrode configurations had initial undrained shear strength of less than 5kPa.

For the test with R4 electrode configuration, final undrained shear strength at the surface is 41kPa. Near the anode, final undrained shear strength is 44kPa and 20kPa at T2 and T3 respectively. Near the cathode, final undrained shear strength is 16kPa and 9kPa at T2 and T3 respectively. For the other anodes of the R4 test, final undrained shear strength ranges from 13 to 18kPa. Final undrained shear strength ranges from 18 to 36kPa and 12 to 20kPa near the anode and cathode respectively. The higher strength gain near the anode and lower strength gain near the cathode observed in the small scale tests is also seen in the large scale tests. At the area between the anodes, final undrained shear strength ranges from 8 to 22kPa and 10 to 24kPa near the test tank wall and drainage well respectively. The final undrained shear strength of the R4 test shows similar trend to the reduction in moisture content, with higher strength gain at the top of the test peat compared to that at the bottom.

For the R6 electrode configuration test, final undrained shear strength at the surface is 15kPa. Final undrained shear strength ranges from 5 to 8.5kPa and 7.5 to 10.5kPa near the anode and cathode respectively. The bottom (T3) of the peat underwent lowest improvement in shear strength, attributed to the visibly wet peat observed at the end of the test. For the other anodes in the R6 test, final undrained shear strength at the peat surface ranges from 9 to 12kPa. Final undrained shear strength ranges from 7.5 to 13kPa and 3.5 to 13kPa near the anode and cathode respectively. Although the moisture content reduction of the R6 test is comparable to that of the R4 test, the strength gain of the R6 test is not as high as the R4 test.

5.7.2 Undrained shear strength of peat at voltage gradient of 100V/m

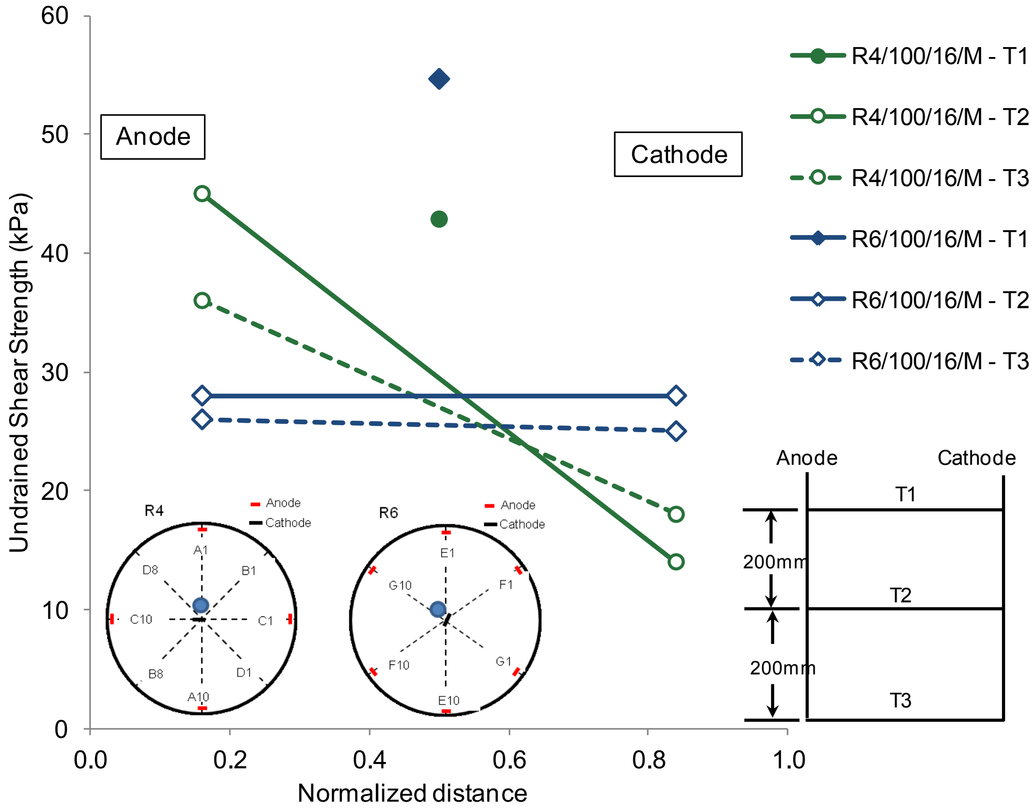


Figure 5.23: Final undrained shear strength of peat in EO tests with R4 and R6 electrode configurations at voltage gradient of 100V/m

Figure 5.23 shows the final undrained shear strength along A1-A5 in the R4 test and E1-E5 in the R6 test for voltage gradient of 100V/m. Appendix A 49 shows all the data for final undrained shear strength for test with R4 electrode configuration. Appendix A 50 presents all the data for final undrained shear strength for test with R6 electrode configuration. Both tests with R4 and R6 electrode configurations had initial undrained shear strength of less than 2kPa.

For the R4 electrode configuration test, final undrained shear strength at peat surface is 43kPa. Near the anode, final undrained shear strength is 45kPa and 36kPa at T2 and T3 respectively. In the vicinity of the cathode, the final undrained shear strength is 14kPa and 18kPa at T2 and T3 respectively. Final undrained shear strength at peat surface for the other sections ranges from 28 to 46kPa. At the other anodes of the R4 test, final undrained shear strength ranges from 41 to 62kPa and 20 to 28kPa near the anode and cathode respectively. In the areas without anodes, the final undrained shear strength ranges from 18 to 33kPa and 16 to 28kPa near the test tank wall and drainage well respectively. The higher undrained shear strength at the peat surface is in agreement with the higher moisture content reduction at the peat surface. As seen in the moisture content reduction earlier, the strength gain also shows reduction with depth.

For the R6 electrode configuration test, final undrained shear strength at peat surface is 55kPa. At T2 and T3, the final undrained shear strength is 28kPa and 26kPa; and 28kPa and 25kPa near the anode and cathode respectively. Along E1-E5, final undrained shear strength at T2 and T3 show a similar range. Other final undrained shear strength at peat surface ranges from 42 to 72kPa. For the other anodes of the R6 test, final undrained shear strength ranges from 35 to 56kPa and 22 to 31kPa near the anode and cathode respectively. Along the other sections, larger variations are observed in the strength gain of the region near the anode and cathode. Noticeably higher final undrained shear strength is observed near the anode compared to that of the area near the cathode. The overall undrained shear strength of the R6 test is relatively higher than that of the R4 test. This is reflected in the higher moisture content reduction of the R6 test.

5.7.3 Undrained shear strength of peat at voltage gradient of 120V/m

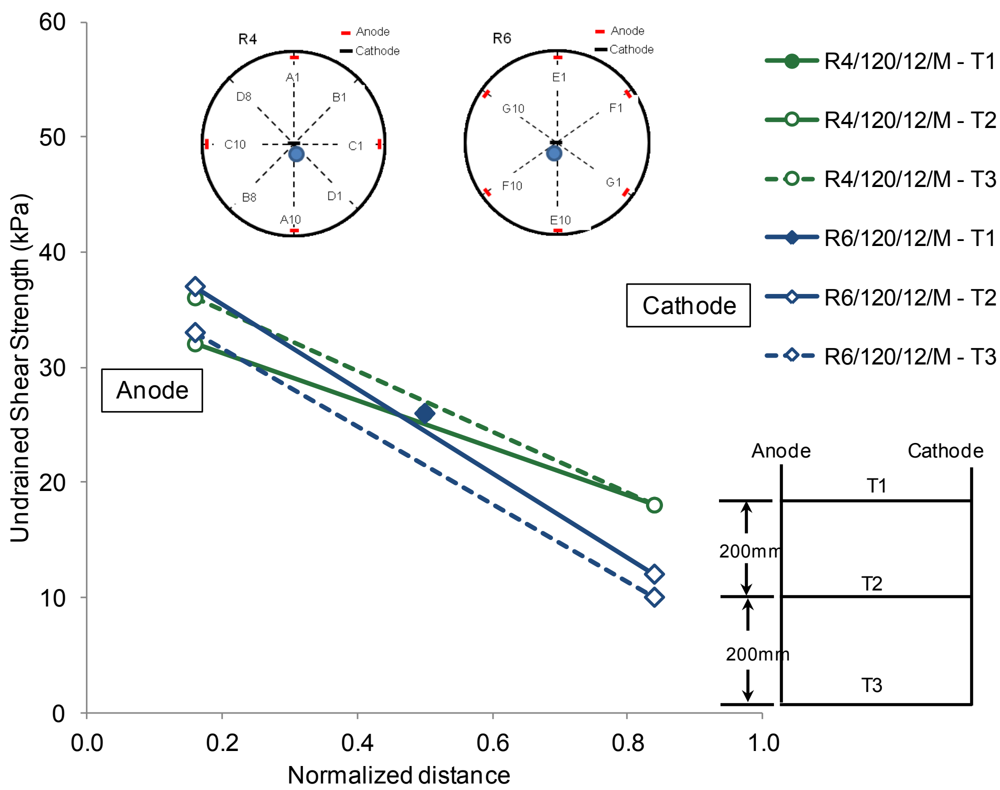


Figure 5.24: Final undrained shear strength of peat in EO tests with R4 and R6 electrode configurations at voltage gradient of 120V/m

Figure 5.24 shows the final undrained shear strength at the surface (T1), mid-depth (T2) and bottom (T3) of the peat along A1-A5 in the R4 test and E1-E5 in the R6 test. Appendix A 69 shows all the data for final undrained shear strength for test with R4 electrode configuration. Appendix A 70 presents all the data for final undrained shear strength for test with R6 electrode configuration. Both tests with R4 and R6 electrode configurations had initial undrained shear strength of less than 2kPa.

In the R4 electrode configuration test, the final undrained shear strength at peat surface is 26kPa. Final undrained shear strength is 32kPa and 36kPa at T2 and T3 near the anode. Near the cathode, final undrained shear strength is 18kPa at both T2 and T3. The other final undrained shear strength at peat surface ranges from 24 to 45kPa. For the other anodes of the R4 test, final undrained shear strength ranges from 32 to 74kPa and 17 to 34kPa near the anode and cathode respectively. Along the sections without anodes, final undrained shear strength ranges from 12 to 32kPa and 13 to 36kPa near the test tank wall and drainage well respectively.

For the R6 electrode configuration test, final undrained shear strength at peat surface is 26kPa. Near the anode, final undrained shear strength is 37kPa and 33kPa at T2 and T3 respectively. Near the cathode, final undrained shear strength is 12kPa and 10kPa at T2 and T3 respectively. At the other sections in the R6 test, the final undrained shear strength at peat surface ranges from 25 to 41kPa. At the other anodes, final undrained shear strength ranges from 29 to 53kPa near the anode and 10 to 28kPa near the cathode. In the R6 test, strength gain near the cathode is lower than that of the R4 test.

5.8 Chapter Summary

This chapter presented the observations and findings for the series of tests carried out to investigate the effects of radial electrode configurations on EO consolidation. Two radial electrode configurations, namely the square (R4) and hexagon (R6) were used in the large scale test setup. The square (R4) electrode configuration is made up of a central cathode surrounded by 4 anodes. The hexagon electrode configuration consists of a central cathode surrounded by six

(6) anodes. Applied voltage gradients were 80V/m, 100V/m and 120V/m for each respective set of tests.

In the tests with voltage gradient of 80V/m, the overall settlement of the R4 electrode configuration test is 1.3% higher than the overall settlement of the R6 electrode configuration test. For the tests with voltage gradient of 100V/m, the overall settlement of the R6 electrode configuration test is 0.6% higher than that of the R4 electrode configuration test. With voltage gradient of 120V/m, the overall settlement of the R4 electrode configuration test is 0.4% higher than the overall settlement of the R6 electrode configuration test. No significant difference in settlement is observed between the R4 and R6 electrode configuration tests.

Both the R4 and R6 electrode configuration tests show higher flow at the earlier stage of the test and reduction in flow at the later stage of the test. Peak flow occurred on the second day of testing. At voltage gradient of 80V/m, the volume of water collected in the R4 and R6 tests show no significant difference with only 0.5% higher total volume of water in the R4 test. For voltage gradient of 100V/m, the R6 test shows a 10% higher total volume of water than the R4 test. With voltage gradient of 120V/m, minimal difference is also observed in the total volume of water collected. R4 test shows 2.5% higher total volume of water collected than the R6 test.

Initial pH of the water collected in the drainage well before the start of EO tests are lower than 7. After application of DC, pH of the water collected shows significant increase to values ranging between 9.5 to 12.13 for the R4 and R6 electrode configuration tests. No significant difference is observed between the pH of water collected in the R4 and R6 tests. In the R4 and R6 tests with voltage gradient of 120V/m, reduction in pH of the water collected is observed. This is attributed to the reduction in electrolysis process as a result of reduction in moisture content of peat.

Both the R4 and R6 electrode configuration tests show higher reduction in moisture content at the peat surface and decreasing moisture content reduction with depth. Reduction in moisture content near the anode is higher than the reduction in moisture content near the cathode. At voltage gradient of 80V/m, reduction in moisture content ranges from 9 to 33% and 16 to 38% for R4 and R6 respectively. In the tests with voltage gradient of 100V/m, reduction in moisture content ranges from 14 to 40% and 8 to 52% for R4 and R6 respectively. For tests with voltage gradient of 120V/m, reduction in moisture content ranges from 0.6 to 46% and 10 to 40% for R4 and R6 respectively.

Higher strength gain is seen near the anode in comparison to the cathode for both R4 and R6 electrode configuration tests. The improvement in shear strength also shows reduction with depth. For voltage gradient of 80V/m, final undrained shear strength ranges from 8 to 44kPa and 5 to 15kPa for R4 and R6 respectively. At voltage gradient of 100V/m, final undrained shear strength ranges from 16 to 62kPa and 22 to 72kPa for R4 and R6 respectively. In the tests with voltage gradient of 120V/m, final undrained shear strength ranges from 13 to 62kPa and 10 to 53kPa for R4 and R6 respectively.

For the R4 and R6 electrode configuration tests, voltage losses are observed near the electrodes, with the losses near the anodes showing increment with time. This is attributed to the movement of water away from the anode and reducing the conductivity in its vicinity. Higher voltage gradient resulted in higher current through peat in both R4 and R6 electrode configuration tests.

In the test with voltage gradient of 80V/m, the overall resistance of the R4 electrode configuration test did not show any noticeable trend. The overall resistance of the R6 electrode configuration test shows increase with time. The resistance of peat, reflected in the resistances of the middle region, shows the lowest ranges compared to the resistance near the electrodes. Resistances near the anode increases with time, attributed to the movement of water away from the anode. No significant difference is observed for the resistance at the electrodes for R4 and R6 tests with voltage gradients of 100V/m and 120V/m. With higher voltage gradients of 100V/m and 120V/m, the resistance of peat shows similar ranges to that of the tests with voltage gradient of 80V/m. This indicates that the resistance of peat did not show significant increase with the increase in voltage gradient.

Further comparisons were carried out with the same electrode configuration at voltage gradients of 80V/m, 100V/m and 120V/m. Comparison of R4 electrode configuration tests with voltage gradients of 80V/m, 100V/m and 120V/m at 192hr shows that settlement is lowest at voltage gradient of 120V/m. The highest settlement is in test with voltage gradient of 100V/m, with 1.8% higher than the settlement at voltage gradient of 120V/m. R4 test with voltage gradient of 80V/m shows marginally lower settlement than that of the test with voltage gradient of 100V/m.

Comparison of the R6 electrode configuration tests with voltage gradients of 80V/m, 100V/m and 120V/m at 192hr also shows lowest settlement in the test with voltage gradient of 120V/m. Highest settlement is observed in the test with voltage gradient of 100V/m, which is 3.1% higher than that in the test with voltage gradient of 120V/m. For the R6 tests, the test with voltage gradient of 80V/m is marginally higher than that of the test with voltage gradient of 120V/m.

Comparison of the R4 electrode configuration tests at voltage gradients of 80V/m, 100V/m and 120V/m at 192hr, highest total volume of water is observed in the test with voltage gradient of 120V/m. This is inconsistent with the settlement of the three tests at 192hr. The R4 test with voltage gradient of 80V/m had highest initial moisture content. However, no significant effect of the higher initial moisture content on EO flow during EO tests on peat.

Comparison of the R6 electrode configuration tests at voltage gradients of 80V/m, 100V/m and 120V/m at 192hr shows highest total volume of water collected at voltage gradient of 100V/m. This is reflected in the highest settlement of the R6 test with voltage gradient of 100V/m at 192hr. For the R6 tests, highest initial moisture content is in the test with voltage gradient of 80V/m. Similar to the R4 tests, no significant effect of higher initial moisture content on EO flow is observed.

The further comparisons show that both the R4 and R6 electrode configurations show highest settlement at 192hr with voltage gradient of 100V/m. The highest volume of water collected at 192hr is observed in the R6 test at voltage gradient of 100V/m. This possible maximum voltage gradient where the highest settlement is achieved is also observed in earlier small scale and large scale tests with voltage gradients of 80V/m, 100V/m and 120V/m.

6 Effect of Pumping Interval and Polarity Reversal on EO Consolidation of Organic Soil and Peat

6.1 Introduction

This series of tests was carried out using the small scale test setup with 2anode-1cathode configuration. Drainage well was included in the test setup. This is done to study the effect of pumping interval on EO flow. Polarity reversal is included during EO consolidation to study the improvement in organic soil and peat. Results of the EO tests are presented in this chapter. Discussions on the observations and findings for the tests are also included in this chapter.

6.2 Effect of pumping interval during EO test on surface settlement in organic soil and peat

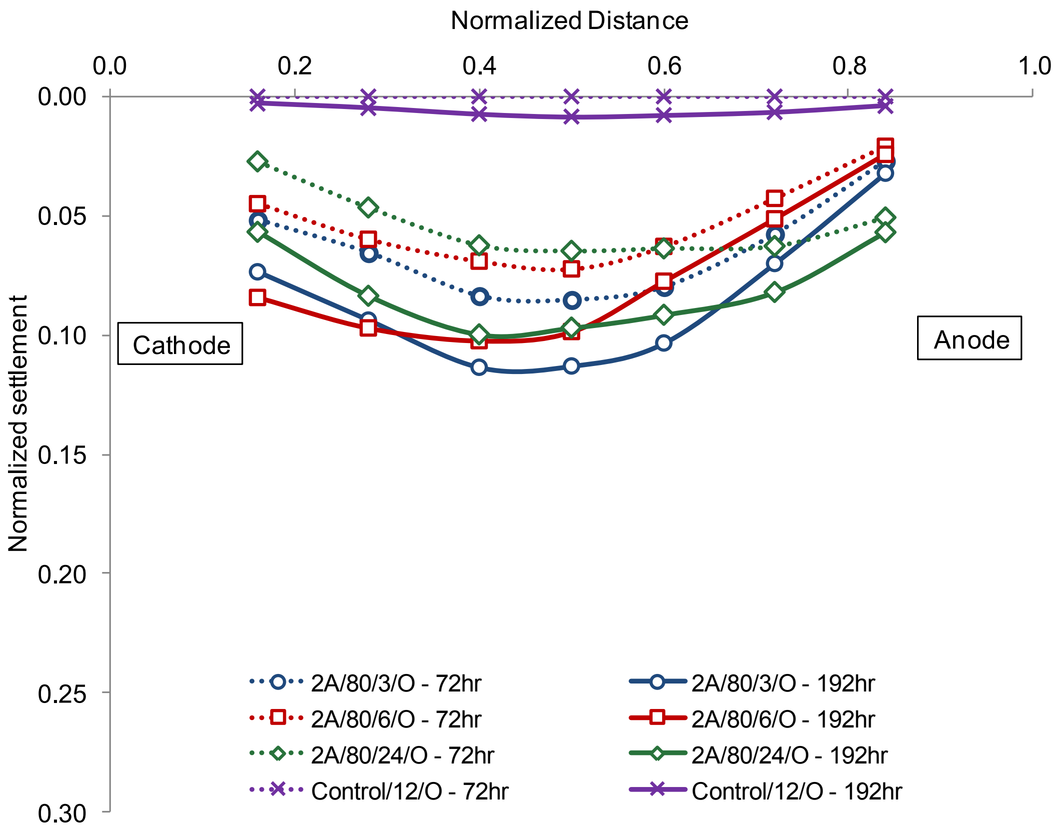
To study the effect of pumping interval during EO, several pumping intervals were chosen. In organic soil, the pumping intervals chosen were 3hr, 6hr and 24hr. While for peat, the pumping intervals were 3hr and 6hr. The 24hr pumping interval was deemed unsuitable for peat due to the high initial moisture content of peat and possible overflowing of the drainage well. Voltage gradient was 80V/m for both organic soil and peat. A control test without application of DC was also included for organic soil and peat.

Figure 6.1: Plan view of small scale EO test setup

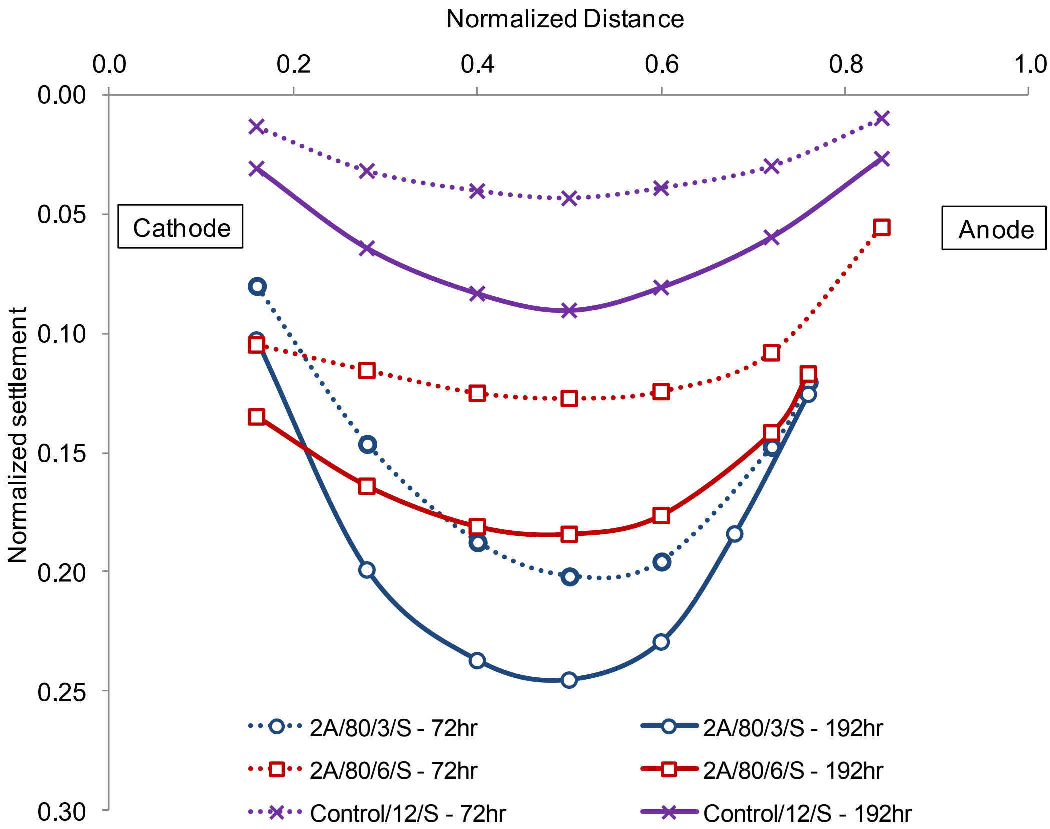
Figure 6.1 shows the plan view of the small scale EO test setup. In the test with organic soil, the initial moisture content was 221%, 221%, 219% and 239% for control test and tests with 3hr, 6hr and 24hr pumping intervals respectively. Initial average undrained shear strength was 2.12kPa, 1.99kPa, 2.65kPa and 2.12kPa for control test and tests with 3hr, 6hr and 24hr pumping intervals respectively. Details of this test series are tabulated in Table 3.3.

For tests on peat, the initial moisture content was 663%, 654% and 667% for control test and tests with 3hr and 6hr pumping intervals respectively. Initial average undrained shear strength was 0.92kPa, 1.05kPa and 1.60kPa for control test and tests with 3hr and 6hr pumping intervals respectively. Further details of the test series are tabulated in Table 3.3.

6.2.1 Surface settlement of organic soil and peat during EO tests



(a)



(b)

Figure 6.2: Normalized settlement profile with time during EO tests on (a) organic soil and (b) peat with different pumping intervals

Figure 6.2(a) shows the normalized settlement profile with time for EO tests on organic soil. Measured soil settlement is normalized using initial height (200 mm) of the organic soil test bed. At 72hr of the test, the control test without application of DC shows the lowest normalized settlement as expected. No noticeable settlement is observed in the control test. In the test with application of DC, the maximum normalized settlement is 0.085, 0.072 and 0.065 for test with 3hr, 6hr and 24hr pumping intervals respectively. Largest normalized settlement occurred in the test with 3hr pumping interval.

At the end of the test at 192hr, the control test continues to show the lowest normalized settlement with only 0.008 or 0.8%. Maximum normalized settlement is 0.113, 0.102 and 0.100 for tests with 3hr, 6hr and 24hr pumping intervals respectively. Test with 3hr pumping interval continues to show the largest settlement. The maximum normalized settlement of the 3hr pumping interval test is 13% higher than that of the 24hr pumping interval test.

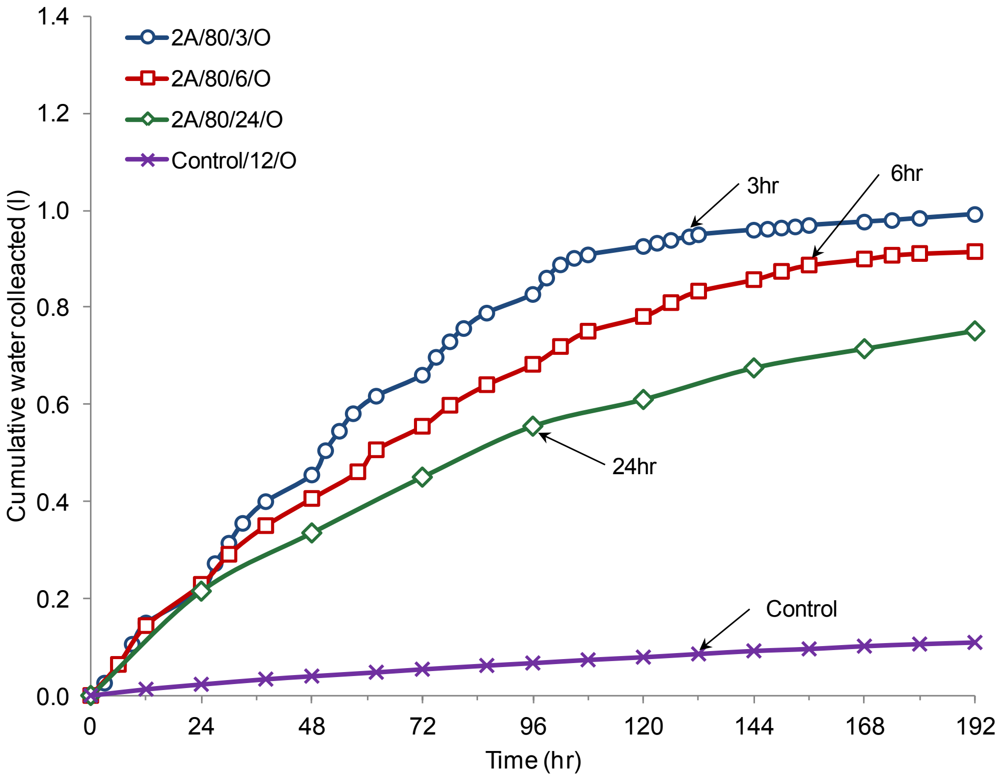
Figure 6.2(b) shows the normalized settlement profile with time in peat during EO tests with 3hr and 6hr pumping intervals. After 72hr, the maximum normalized settlement of the control test is 0.04. While after 72hr of application of DC, the maximum normalized settlement is 0.20 and 0.13 for test with 3hr and 6hr pumping intervals respectively. The test with 3hr pumping interval shows the largest normalized settlement at 72hr.

At the end of the test, the control test shows a maximum normalized settlement of 0.09. In the tests with 3hr and 6hr pumping intervals, the maximum normalized settlement is 0.24 and 0.18 respectively. With a 0.04 increase in settlement between 72hr to 192hr, test with 3hr pumping interval shows higher settlement rate before 72hr and reduction in settlement rate after 72hr.

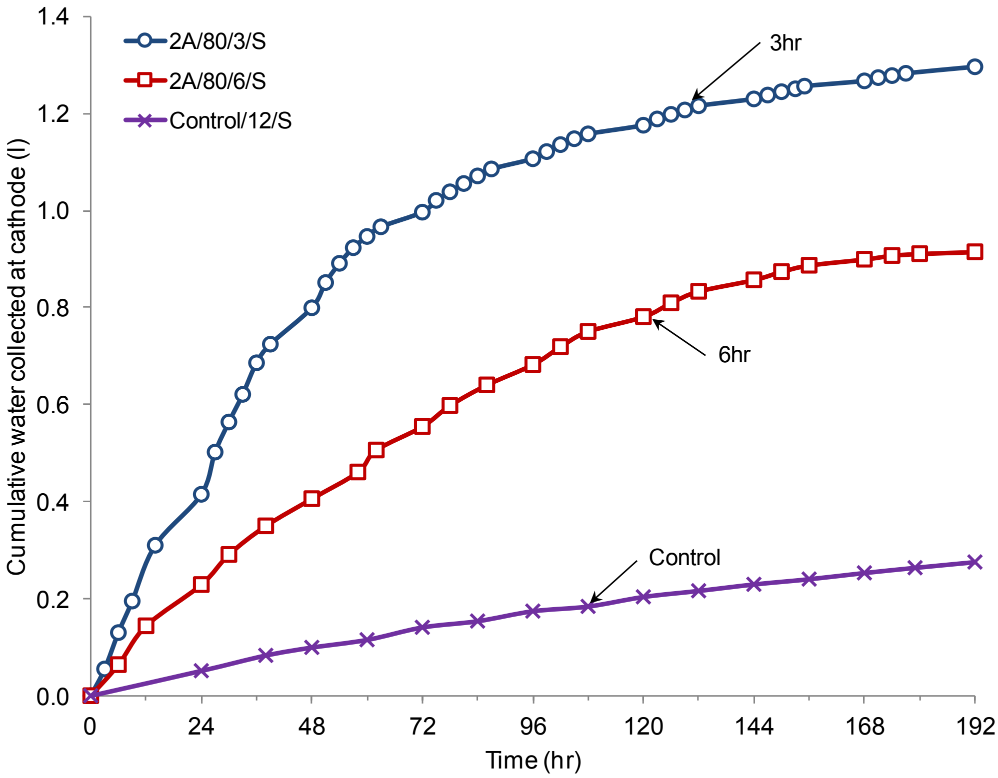
The higher settlement rate of the 3hr pumping interval tests might be attributed to the frequent removal of water collected in the drainage well. The removal of water near the cathode reduces build up of counteracting hydraulic gradient, discussed further in Section 6.2.2. Frequent removal of water collected in the drainage well resulted in higher removal of water from the test bed, hence increasing the settlement.

With the same test setup and applied voltage gradient of 80V/m on organic soil and peat, settlement in peat is of a higher magnitude compared to the settlement in organic soil. At times, the maximum settlement of peat is nearly 2 times the maximum settlement of organic soil for the same time interval. This reflects the high compressibility of peat. The series of tests with varied pumping intervals on organic soil and peat show that 3hr pumping interval resulted in the highest degree of settlement.

6.2.2 Water collected during EO test on organic soil and pest



(a)



(b)

Figure 6.3: Cumulative water collected during EO tests on (a) organic soil and (b) peat with different pumping intervals

Figure 6.3(a) shows the cumulative volume of water collected in the tests with organic soil. For the control test, water in the drainage well was removed at 12-hour intervals. Water collected overnight in the drainage well after preparation of the test tanks was removed before the start of the tests. In the control test, water collected before the start of the test was 28mℓ. Flow in the control test is low with total volume of water collected of 0.11ℓ. Flow in the control test is less than 15mℓ over a 12-hour period.

For the tests with pumping intervals, volume of water collected before the application of DC was 23mℓ, 23mℓ and 19mℓ for tests with 3hr, 6hr and 24hr pumping intervals respectively. Total volume of water collected is 0.99ℓ, 0.91ℓ and 0.75ℓ for test with 3hr, 6hr and 24hr pumping intervals respectively. Highest volume of water collected is in the test with 3hr pumping interval while lowest volume of water collected is in the test with 24hr pumping interval. All three EO tests show gradual reduction of flow with time. Total volume of water collected from test with 3hr pumping interval is 1.3 times of that in the test with 24hr pumping interval.

Viggiani and Squeglia (2003) conducted a field test on electro-osmotic stabilization of Pancone clay. Pore pressure transducers were included in the field test setup. Results of the field test showed positive excess pore pressure build up in the vicinity of the cathode. This is attributed to the EO flow in the direction of the cathode. Excess pore pressure build up near the cathode resulted in a counteracting hydraulic gradient in the direction of the anode. To reduce the build up of counteracting hydraulic gradient, Hansbo (2008) recommended removal of water at the cathode. This is in agreement with the results of the pumping interval tests, where the 3hr pumping interval resulted in the highest volume of water collected. The lowest total volume of water collected in the 24hr pumping interval test could be due to higher counteracting hydraulic gradient, resulting in disruption of EO flow in the direction of the cathode.

pH of water collected was measured when a minimum of 50mℓ was collected. For the test with 3hr pumping intervals, pH of water collected ranges from 9.96 to 10.82. pH of the water collected during the test with 6hr pumping intervals ranges from 9.67 to 11.66. pH of the water collected during the test with 24hr pumping interval ranges from 10.71 to 12.16. The test with 24hr pumping interval shows the highest pH range. pH values of the water collected shows an increasing trend with the increase in pumping interval, with the highest range of pH observed in the test with 24hr pumping interval. During electro-osmosis, hydroxides are generated near the cathode and longer pumping intervals resulted in larger accumulation of hydroxides. The increase in hydroxide ion concentration increases pH, reflected in the highest pH range of the water collected in the 24hr pumping interval test.

Figure 6.3(b) shows the cumulative volume of water collected during EO tests on peat with pumping intervals of 3hr and 6hr. In the control test, the water was collected at 12-hour intervals. For the control test, water collected before the start of the test was 58mℓ and total volume of water collected is 0.27ℓ. Flow in the control test is the lowest, which is in agreement with the lowest settlement observed. In the control test, flow at 12-hour intervals is less than 30mℓ and shows a gradually decreasing trend with time.

In the tests with application of DC, flow of water is greatly increased. 34mℓ and 23mℓ of water was collected before the start of test with 3hr and 6hr pumping intervals respectively. Total volume of water collected is 1.30ℓ and 0.94ℓ in the test with 3hr and 6hr pumping intervals respectively. The high EO flow at the start of the 3hr pumping interval test is reflected in the higher settlement rate observed in Figure 6.2(b). Highest volume of water collected is in the test with 3hr pumping interval. This is similar with the pumping interval tests in organic soil. With a shorter pumping interval, the build up of counteracting hydraulic gradient is lower. This in turn reduces disruption in EO flow toward the cathode.

Wherever possible, the pH of the water collected was measured. pH of the water collected during the 3hr pumping interval test ranges from 9.76 to 10.85. pH of the water collected in the 6hr pumping interval ranges from 6.98 to 10.02. The pH of the water collected in the 6hr pumping interval test shows values lower than pH 8, which is not consistent with a longer pumping interval.

6.2.3 Moisture content after EO tests on organic soil and peat

The final moisture content of organic soil and peat were obtained at 7cm, 12.5cm and 18cm from the cathode. Soil samples were collected in Shelby tubes at each location. The organic soil sample was then extruded and divided into segments to obtain final moisture contents at different depths. Initial moisture content of the organic soil was 221%, 221%, 219% and 239% for control test and tests with 3hr, 6hr and 24hr pumping intervals respectively. Initial moisture content of the peat was 663%, 654% and 667% for control test and tests with 3hr and 6hr pumping intervals respectively

Table 6.1 presents the final moisture content in the tests on organic soil. In the control test, final moisture content ranges from 201 to 212%. Minimal change is observed in the moisture content of the control test. Relatively lower moisture content is observed near the drainage well. For test with 3hr pumping intervals, final moisture content ranges from 126 to 134%, 144 to 157% and 160 to 176% near the anode, at the middle and near the cathode respectively. With 6hr pumping intervals, final moisture content ranges from 131 to 148%, 164 to 169% and 179 to 192% near the anode, at the middle and near the cathode respectively. In the 24hr pumping interval test, the final moisture content ranges from 167 to 170%, 174 to 181% and 186% to 204% near the anode, at the middle and near the cathode respectively. All three EO tests show lower final moisture content near the anode and higher final moisture content near the cathode. Test with 3hr pumping intervals shows the lowest range of final moisture content while test with 24hr pumping interval shows the highest range.

Table 6.1 also shows the percentage of reduction in moisture content. The percentage of reduction in moisture content is calculated as the percentage of change in moisture content over the initial moisture content. The control test shows little reduction in moisture content. The percentage of moisture content reduction ranges from 5 to 9%. In the test with 3hr pumping interval, percentage of reduction in moisture content ranges from 39 to 43%, 29 to 35% and 20 to 28% near the anode, the middle and near the cathode respectively. For the test with 6hr pumping interval, percentage of reduction in moisture content ranges from 32 to 40%, 23 to 25% and 12 to 18% near the anode, the middle and near the cathode respectively. In the test with 24hr pumping interval, percentage of reduction in moisture content ranges from 29 to 30%, 24 to 27% and 15 to 22% near the anode, at the middle and near the cathode respectively. Highest reduction in moisture content is observed in the test with 3hr pumping interval. This is in agreement with the highest total volume of water collected of the same test. Highest moisture content reduction is observed near the anode for all three EO tests with pumping intervals, reflecting the EO flow from the anode toward the cathode.

Table 6.2 shows the final moisture content of the tests on peat. In the control test, final moisture content ranges from 572 to 650% with no significant reduction in moisture content. For the test with 3hr pumping interval, final moisture content ranges from 430 to 468%, 457 to 477% and 495 to 513% near the anode, at the middle and near the cathode respectively. In the test with 6hr pumping interval, final moisture content ranges from 435 to 479%, 448 to 478% and 460 to 508% near the anode, at the middle and near the cathode respectively. Lower final moisture contents near the anode and higher final moisture contents near the cathode is also observed in the EO tests on peat. Test with 3hr pumping interval shows the lowest range of final moisture content, reflecting the highest total volume of water collected. This is similar to the test with 3hr pumping interval in organic soil.

Table 6.2 also shows the percentage of reduction in moisture content in peat. Lowest reduction in moisture content is observed in the control test, ranging from 2 to 14%. In the test with 3hr pumping interval, the percentage of reduction in moisture content ranges from 28 to 34%, 27 to 30% and 22 to 24% near the anode, at the middle and near the cathode respectively. For the test with 6hr pumping interval, percentage of reduction in moisture content ranges from 28 to 35%, 28 to 33% and 24 to 31%. The percentage of reduction in moisture content of the 3hr pumping interval test does not show a higher range than that of the 6hr pumping interval test. This is inconsistent with the highest volume of water collected in the 3hr pumping interval test.

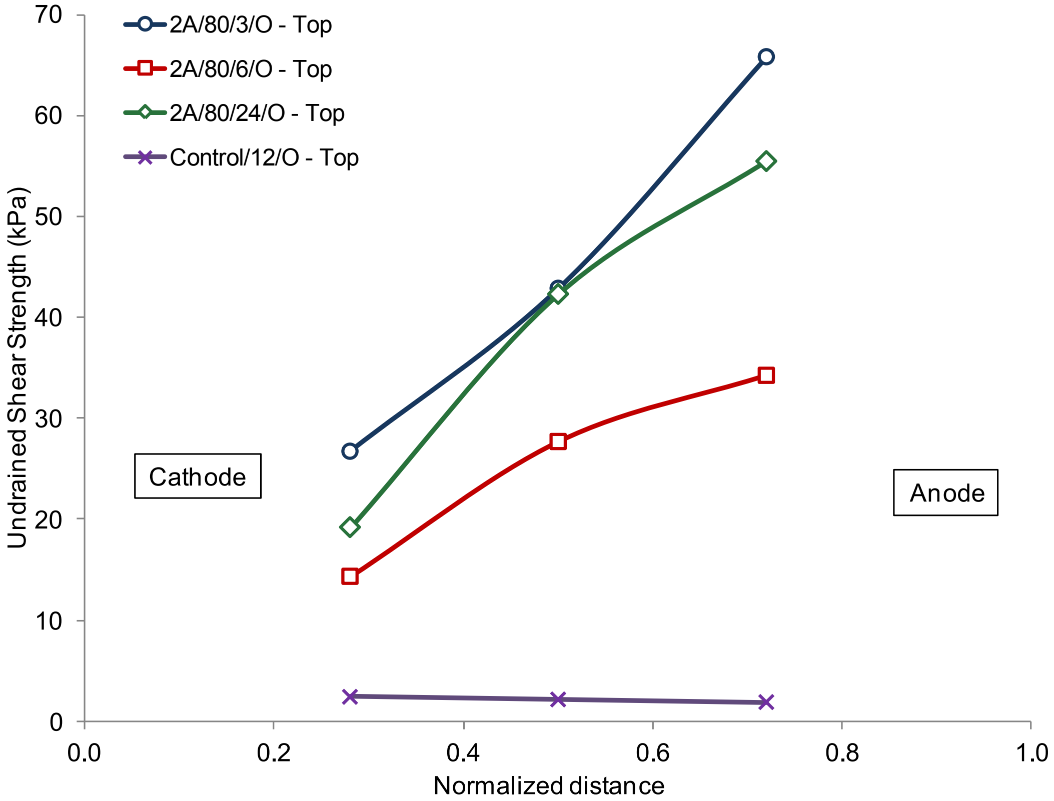
Table 6.1: Comparison of final moisture content post EO tests on organic soil with varied pumping intervals

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
Control/12/O	221	201	211	206	9	5	7	0 – 3 cm
		206	211	209	7	5	5	3 - 6 cm
		206	212	211	7	5	5	6 – 9 cm
		206	212	211	7	5	5	9 - 13 cm
2A/80/3/O	221	176	157	129	20	29	42	0 – 4.5 cm
		170	148	129	23	33	42	4.5 - 9 cm
		162	144	126	27	35	43	9 – 13.5 cm
		160	144	134	28	35	39	13.5 - 17 cm
2A/80/6/O	219	192	169	148	12	23	32	0 - 4 cm
		184	164	142	16	25	35	4 - 8 cm
		181	165	132	17	25	40	8 - 12 cm
		179	164	131	18	25	40	12 - 17 cm
2A/80/24/O	239	204	181	170	15	24	29	0 – 2 cm
		204	175	169	15	27	29	2 - 4 cm
		193	174	167	19	27	30	4 – 6 cm
		186	-	-	22	-	-	6 - 10 cm

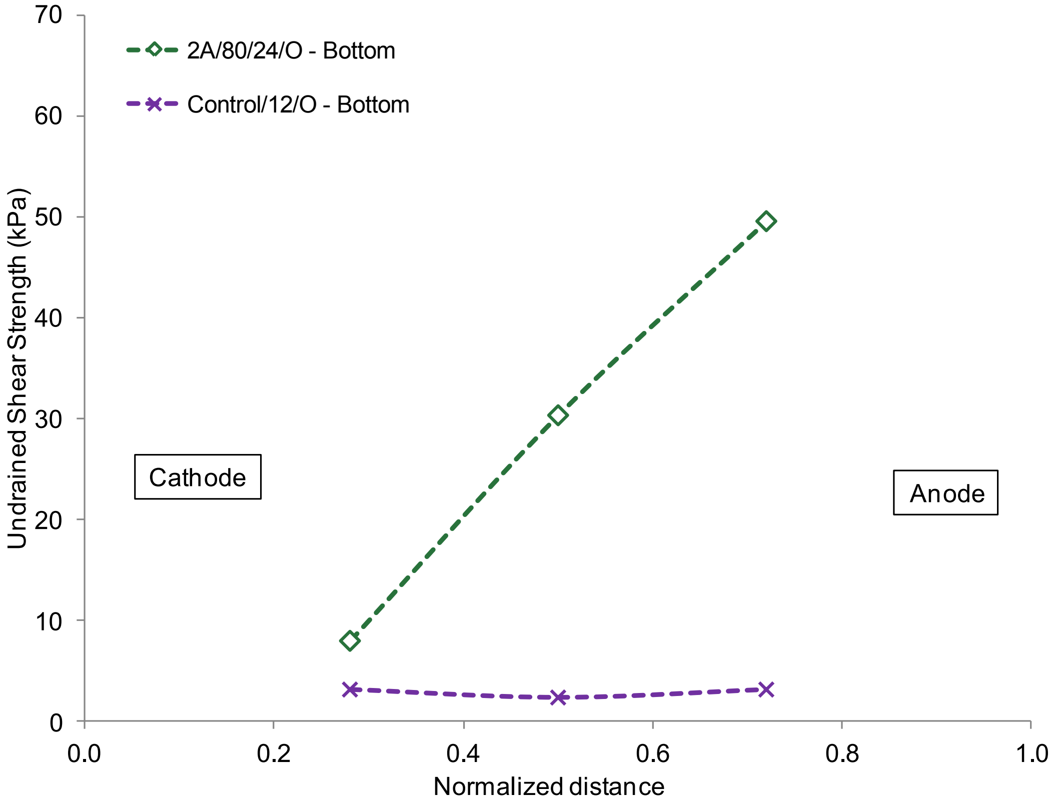
Table 6.2: Comparison of final moisture content post EO tests on peat with 3hr and 6hr pumping intervals

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
Control/12/S	663	593	608	572	11	8	14	0 – 3 cm
		606	650	608	9	2	8	3 - 6 cm
		611	619	611	8	7	8	6 – 9 cm
		-	-	613	-	-	8	9 - 11 cm
2A/80/3/S	654	501	457	430	23	30	34	0 – 3 cm
		499	465	445	24	29	32	3 - 6 cm
		495	477	460	24	27	30	6 – 9 cm
		513	475	468	22	27	28	9 - 12 cm
2A/80/6/S	667	508	466	479	24	30	28	0 – 3 cm
		493	478	469	26	28	30	3 - 6 cm
		460	459	451	31	31	32	6 – 9 cm
		-	448	435	-	33	35	9 - 12 cm

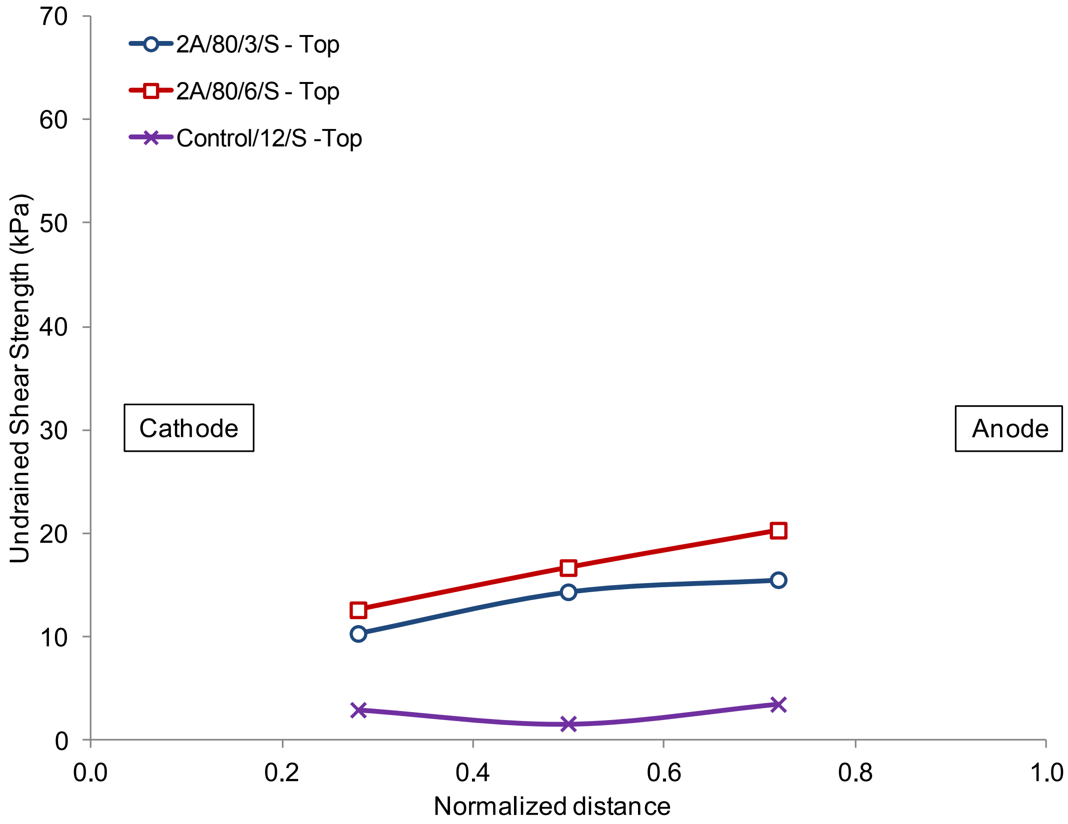
6.2.4 Undrained shear strength of organic soil and peat after EO tests



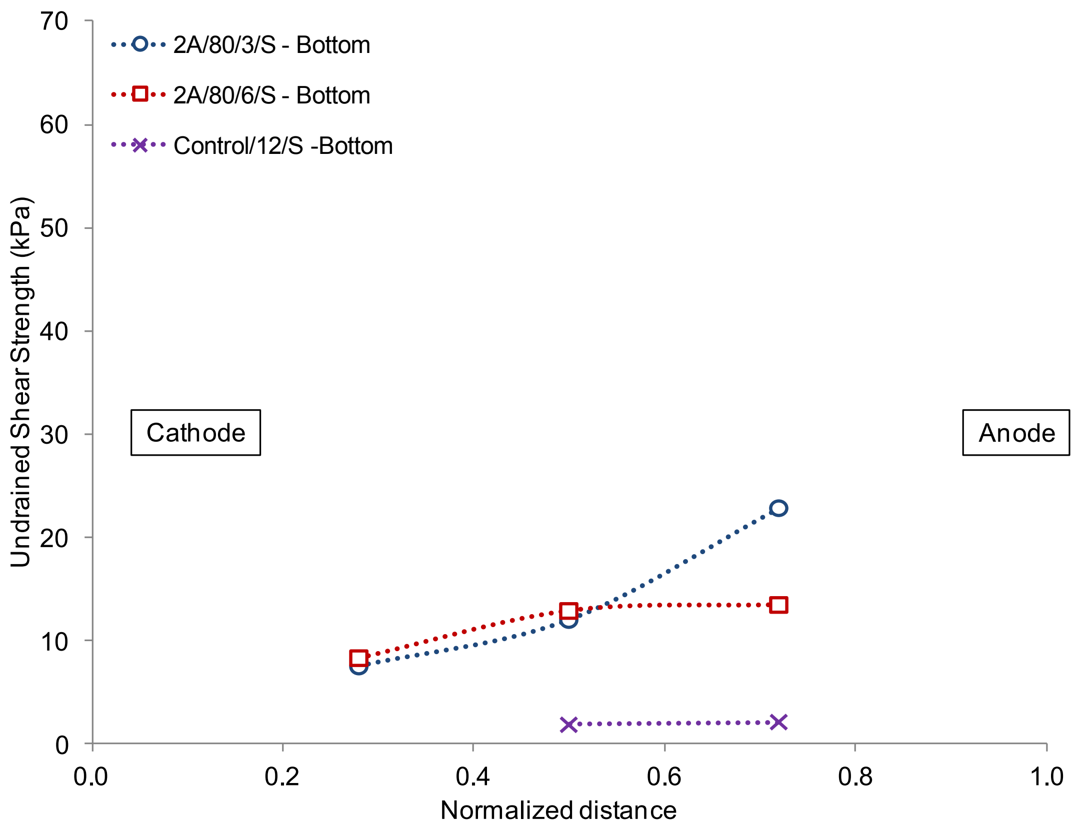
(a)



(b)



(c)



(d)

Figure 6.4: Final undrained shear strength at (a) top and (b) bottom of organic soil; and (c) top and (d) bottom of peat test bed after EO tests

Final undrained shear strength after EO test was conducted at 0.28, 0.55 and 0.72 normalized distances from the cathode. Laboratory vane shear tests were carried out at the top and bottom of the test bed. Figure 6.4(a) shows the final undrained shear strength at the top of the organic soil bed. Initial undrained shear strengths of the organic soil were less than 3kPa. Final undrained shear strength of the control test is low, ranging from 1.86 to 2.38kPa. For the test with 3hr pumping interval, final undrained shear strength ranges from 27 to 66kPa, with higher improvement near the anode. Improvement of shear strength near the anode is 2.4 times greater than that near the cathode. In the test with 6hr pumping interval, final undrained shear strength ranges from 14 to 34kPa. For the test with 24hr pumping interval, final undrained shear strength ranges from 19 to 55kPa. The improvement in shear strength of the 6hr pumping interval test is lower than that of the test with 24hr pumping interval. This is inconsistent with the higher volume of water collected in the 6hr pumping interval test.

Figure 6.4(b) shows the final undrained shear strength at the bottom of the organic soil. For the control test, final undrained shear strength ranges from 2.38 to 3.17kPa. No significant improvement is observed in the control test. Final undrained shear strengths for tests with 3hr and 6hr pumping intervals are not available. For the test with 24hr pumping interval, final undrained shear strength ranges from 8 to 49kPa. The low undrained shear strength near the cathode is attributed to the relatively wet soil in the vicinity of the cathode.

Figure 6.4(c) shows the final undrained shear strength at the top of the peat bed. Initial undrained shear strengths of peat were less than 2kPa. In the control test, final undrained shear strengths are less than 4kPa, indicating no significant improvement. In the test with 3hr pumping interval, final undrained shear strength ranges from 10.3 to 15.5kPa. However, the results of the laboratory vane shear tests are inconsistent with the high volume of water removed from the same test. For the test with 6hr pumping interval, final undrained shear strength ranges from 12.6 to 20.3kPa. All the EO tests show higher strength gain near the anode and lower strength gain near the cathode.

Figure 6.4(d) presents the final undrained shear strength at the bottom of the peat. In the control test, the final undrained shear strengths are 1.86kPa and 2.12kPa. The vane shear test was not conducted at 0.28 normalized distance from cathode as the vane could not be inserted into the peat sample due to a mesh of roots. The shear strength of the control test showed no significant improvement. For the test with 3hr pumping interval, final undrained shear strength ranges from 7.5 to 22.8kPa. In the test with 6hr pumping interval, final undrained shear strength ranges from 8.3 to 13.5kPa. The trend of lower strength gain near the cathode and higher strength gain near the anode is also observed at the bottom of the peat.

Both the organic soil and peat in this series of tests show higher strength gain near the anode and lower strength gain near the cathode. The magnitude of strength gain in shear strength of peat is lower compared to organic soil. This is attributed to the higher final moisture content of peat after EO test. The relatively lower final undrained shear strength near the cathode is due to trapped water in the vicinity of the cathode.

6.3 Effect of polarity reversal on EO consolidation of organic soil and peat

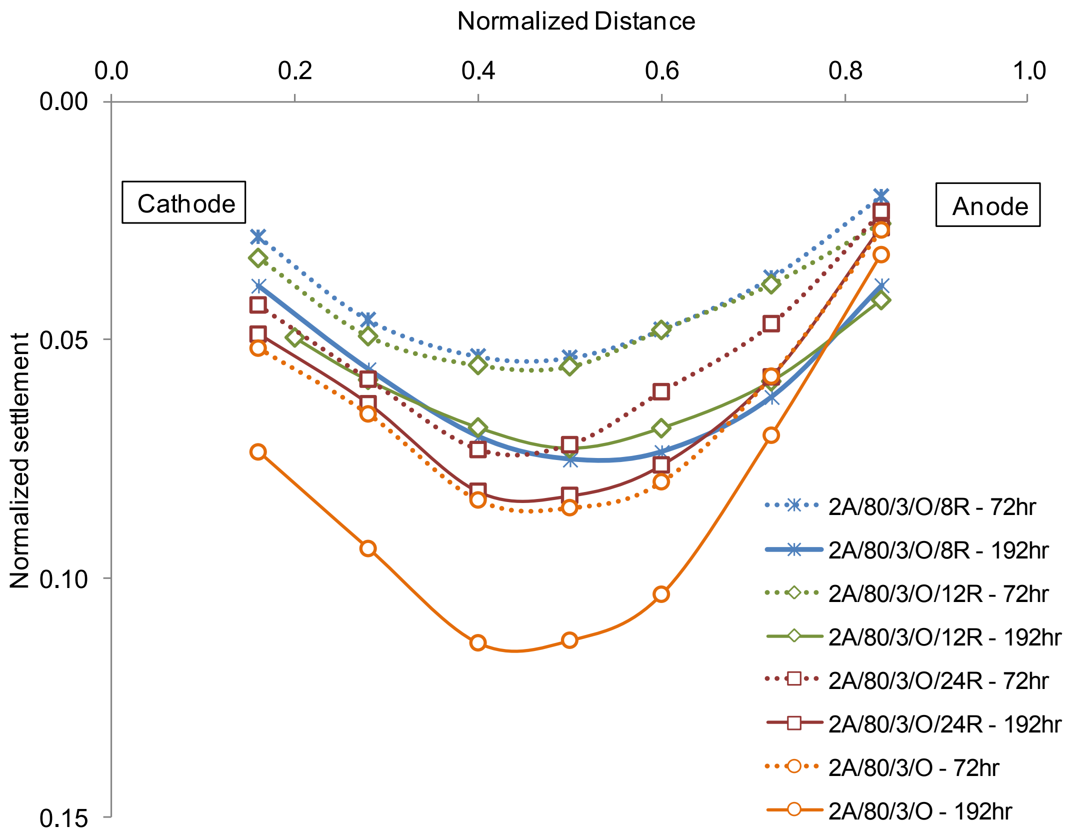
This test series was carried out on organic soil and peat to investigate the effects of polarity reversal during EO consolidation. For organic soil, polarity reversal was carried out at 8hr, 12hr and 24hr intervals. For peat, polarity reversal was carried out at 24hr intervals. Figure 6.5 shows the layout of the small scale test setup for EO tests with polarity reversal on organic soil and peat.

Figure 6.5: Plan view of small scale test setup for tests with polarity reversal

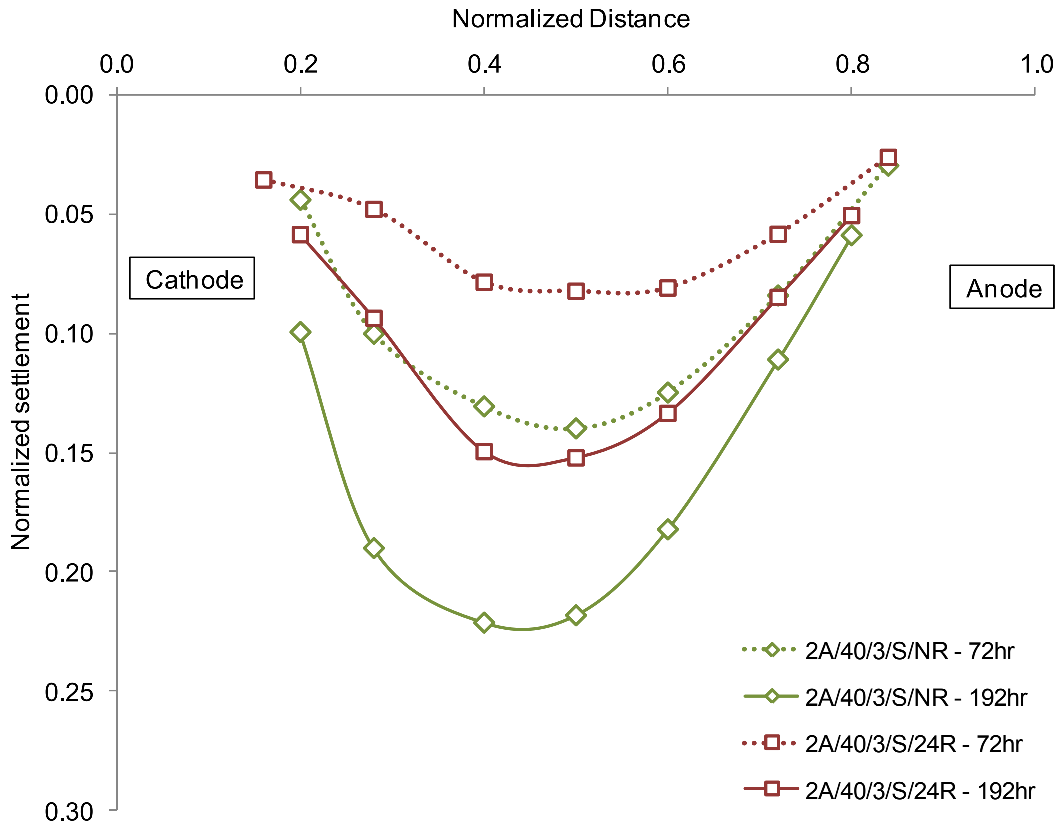
In the tests on organic soil, applied voltage gradient was 80V/m. Initial moisture content was 254%, 249% and 254% for test with 8hr, 12hr and 24hr polarity reversal respectively. Initial undrained shear strength was 0.92kPa, 1.19kPa and 0.92kPa for test with 8hr, 12hr and 24hr polarity reversal respectively. Data from EO test on organic soil conducted earlier without polarity reversal organic soil is included for comparison. Test details are tabulated in Table 3.3.

Test with polarity reversal in peat was carried out with voltage gradient of 40V/m. One test was maintained as fixed polarity without reversal. Initial moisture content was 641% and 650% for test without polarity reversal and test with 24hr polarity reversal respectively. Initial undrained shear strength was 1.06kPa for both tests. Details of this test series are shown in Table 3.3.

6.3.1 Surface settlement of organic soil and peat during EO tests



(a)



(b)

Figure 6.6: Normalized settlement profile with time of (a) organic soil and (b) peat during EO tests with polarity reversal

Figure 6.6(a) shows the normalized settlement profile of organic soil with time during EO tests with polarity reversal. Measured soil settlement is normalized using average initial height of the test soil, 200mm. After 72hr of application of DC, tests with 8hr and 12hr polarity reversal show almost identical settlement. Maximum normalized settlements are 0.054 and 0.055 for 8hr and 12hr polarity reversal tests respectively. In the test with 24hr polarity reversal, settlement occurs at a higher rate with maximum normalized settlement of 0.073. Highest rate of settlement at 72hr is observed in the test with 24hr polarity reversal. In the test without polarity reversal, the maximum normalized settlement of 0.085, is higher than that of the three tests with polarity reversal.

At the end of the test, at 192hr, tests with 8hr and 12hr polarity reversal continue to show similar settlements with maximum normalized settlements of 0.075 and 0.073 respectively. In the test with 24hr polarity reversal, maximum normalized settlement at 192hr is 0.082. For the test without polarity reversal, maximum settlement was 0.113, which is approximately 1.4 times the maximum settlement of the 24hr polarity reversal test.

From literature, polarity reversal was carried out to minimise differential settlement between the cathode and anode region. In the test with 8hr polarity reversal, final settlements near the cathode and anode are 0.039 and 0.038 respectively. The difference between settlements at the two electrodes is minimal at 0.1%. In the tests with 12hr and 24hr polarity reversal, difference between final settlements near the cathode and anode are 0.7% and 2.3% respectively. In the test without polarity reversal, the cathode region underwent higher settlement with a difference of 4.1% between the anode and cathode.

Polarity reversal at shorter intervals of 8hr and 12hr resulted in lower differential settlement. However, application of shorter polarity reversal intervals also resulted in lower overall settlement. Polarity reversal at 24hr intervals in organic soil resulted in larger settlement but with the highest differential settlement among EO tests with polarity reversal. However the magnitude of settlement in the 24hr polarity reversal test is low in comparison to the test without polarity reversal.

Figure 6.6(b) shows the normalized settlement profile with time of peat during EO tests with and without polarity reversal. Measured soil settlement is normalized using average initial height of the test peat, 180mm. At 72hr of the EO tests, larger settlement is observed in the test without polarity reversal. Maximum normalized settlement is 0.014 and 0.008 for test without and with polarity reversal respectively. At the end of the test, maximum normalized settlement is 0.221 and 0.152 for test without and with polarity reversal respectively. The maximum settlement in the test without polarity reversal is 1.45 times greater than that of the test with 24hr polarity reversal.

In the test without polarity reversal, final settlement near the cathode and anode is 0.099 and 0.059 respectively. The difference in settlements near the two electrodes is 0.04 or 4%. In the test with 24hr polarity reversal, final settlement near the cathode and anode is 0.059 and 0.051 respectively, with a difference of 0.8%. Polarity reversal during EO of peat resulted in lower differential settlement between the cathode and anode. However, application of polarity reversal also resulted in lower overall settlement. Similar trend is also observed in the polarity reversal test on organic soil.

6.3.2 Water collected during EO of organic soil and peat

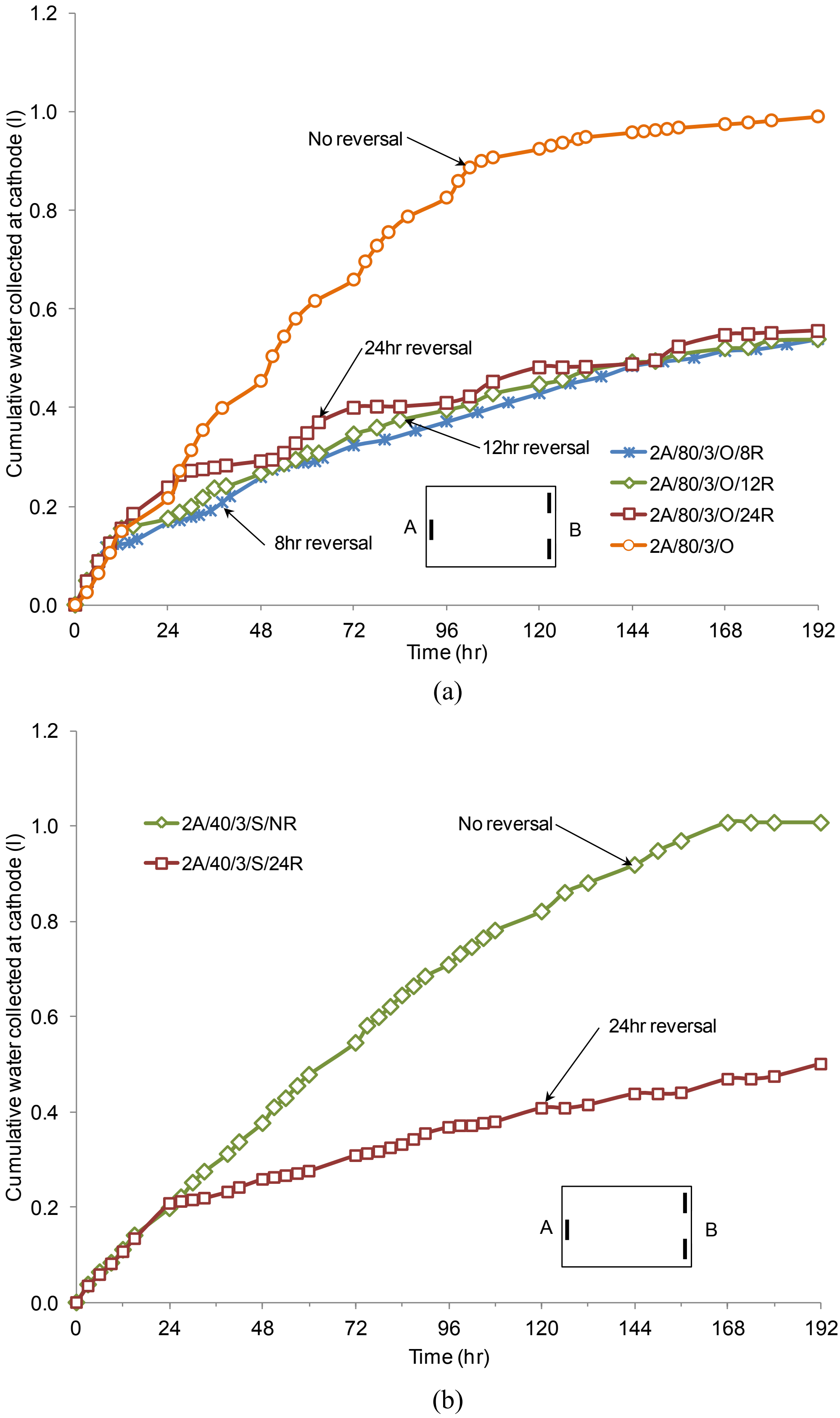


Figure 6.7: Cumulative water collected at the cathode during EO tests on (a) organic soil and (b) peat with polarity reversal

In the tests with polarity reversal, at the start of the EO test, the single electrode at side A was the cathode (see inset) while the 2 electrodes at side B were the anodes. When polarity was first reversed, side A became the anode while side B became 2 cathodes. Later, as the polarity was reversed again, the cathode reverted to side A and anodes at side B. The tests progressed with electrodes at sides A and B alternating as cathode and anode.

Figure 6.7(a) shows the cumulative water collected at the cathode during EO tests on organic soil with polarity reversal. Total volume of water collected is 0.54ℓ, 0.54ℓ and 0.55ℓ for test with 8hr, 12hr and 24hr polarity reversal respectively. The total volume of water collected in the test without polarity reversal was 0.99ℓ. This is approximately 1.8 times the total volume of water collected in each respective polarity reversal test. No significant difference is observed in total volume of water collected for tests with 8hr and 12hr polarity reversal. Highest total volume of water collected in the tests with polarity reversal is from the test with 24hr polarity reversal.

Test with 24hr polarity reversal exhibits more variation in EO flow during the test. First polarity reversal was done at 24hr and the electrodes at side B were now the cathodes. During the first polarity reversal, $53m\ell$ of water was collected. Second polarity reversal was done at 48hr, with the cathode reverting to side A. During the second polarity reversal, EO flow increased and volume of water collected was $108m\ell$. This volume of water is double the amount collected during the first polarity reversal at 24hr. The third polarity reversal was done at 72hr and the cathodes were the electrodes at side B. During the third polarity reversal, only $10m\ell$ of water was collected. The fourth polarity reversal at 96hr sees an increase in the EO flow again. This pattern of alternating high and low EO flow is observed throughout the test duration.

The periods of low EO flow might be attributed to the lower driving force of 1anode (side A) moving water towards 2cathode (side B). The EO test started with 2anode (side B) driving the water toward 1cathode (side A). When polarity was reversed, the electrode configuration became 1anode-2cathode. Hence the movement of ion from the anode toward could be reduced due to the possible lowered driving force from only one anode. Previous study by Kaniraj *et al*. (2011) found that a 2anode-1cathode configuration generated better results over a 1anode-1cathode configuration. This lower driving force with one anode at side A coupled with the possibly drier area at side B might reduce the EO flow.

Figure 6.7(b) shows the cumulative water collected during EO tests on peat without and with polarity reversal. Total volume of water collected is 1.0ℓ and 0.5ℓ in the test without and with polarity reversal. Test with 24hr polarity reversal shows similar flow to the test without polarity reversal for the first 24 hours of the test. This is due to the same test configurations of the two tests, with the cathode at Side A and 2 anodes at Side B. At 24hr, 0.21ℓ of water was collected from the test with 24hr polarity reversal. However, after the first polarity reversal, the volume of water collected shows great reduction. With the first polarity reversal, electrode at Side A was the anode while the two electrodes at Side B were the cathodes. During the first polarity reversal, only 50mℓ of water was collected, which is only a fraction of the water collected in the first 24 hours.

The second polarity reversal was done at 48hr, with the cathode reverting to Side A. After the second polarity reversal, the EO flow in the peat did not show any increment, unlike the trend seen in organic soil. During the second polarity reversal, 50mℓ was collected. Third polarity reversal was done at 72hr and the electrodes at Side B were acting as cathodes. During the third polarity reversal, 59mℓ of water was collected. Fourth polarity reversal at 96hr saw the electrode at Side A acting as the cathode. No significant increase in flow is observed, with 40mℓ water collected. The trend of slow flow and gradual reduction in flow with time is evident from 24hr onwards. Hence with the low flow, the total volume of water collected in the test with polarity reversal is half the total volume of water collected in the test without polarity reversal. Polarity reversal during EO in peat resulted in great reduction in EO flow. This is reflected in the low settlement of the test with polarity reversal.

6.3.3 Moisture content after EO tests on organic soil and peat

Soil samples for moisture content were obtained at 7cm, 12.5cm and 18cm from the cathode in the tests on organic soil and peat. Shelby tubes were used to collect the soil samples. The soil sample extruded from the Shelby tube was divided into segments to obtain the final moisture content at different depths. Initial moisture content for organic soil was 254%, 249% and 254% for test with 8hr, 12hr and 24hr polarity reversal respectively. Initial moisture content for peat was 641% and 650% for test without and with polarity reversal respectively.

Table 6.3 shows the final moisture contents of the EO tests on organic soil with polarity reversal. In the test with 8hr polarity reversal, final moisture content ranges from 205 to 214%, 216 to 227% and 208 to 213% near the anode, at the middle and near the cathode respectively. The final moisture contents near the electrodes are similar. The final moisture content is higher at the middle of the test bed. For the test with 12hr polarity reversal, final moisture content ranges from 215 to 246%, 213 to 234% and 213 to 219% near the anode, at the middle and near the cathode respectively. Near the anode, a higher final moisture content occurred which is inconsistent with the other lower final moisture contents near the anode. For the test with 12hr polarity reversal, higher final moisture content is also observed at the middle of the test bed. Final moisture content of the test with 24hr polarity reversal ranges from 207 to 213%, 210 to 212% and 205 to 213% near the anode, at the middle and near the cathode respectively.

The final moisture contents of the test with 24hr polarity reversal are the lowest among the tests with polarity reversal. This is in agreement with the highest volume of water collected in the same test. The final moisture content of the test with 24hr polarity reversal exhibits minimal variation throughout the test bed. This indicates the uniformity of reduction in moisture content between the anode and the cathode. For the test without polarity reversal, final moisture content ranged from 126 to 134%, 144 to 157% and 160 to 176% near the anode, at the middle and near the cathode. The final moisture content of the test without polarity reversal is lower near the anode and higher near the cathode. This reflected the direction of EO flow from anode to cathode, resulting in non-uniformity of moisture content through the test bed.

Table 6.3 also presents the percentage of moisture content reduction of the organic soil, which is calculated as the percentage of change in moisture content over the initial moisture content. In the test with 8hr polarity reversal, the percentage of moisture content reduction ranges from 15 to 19%, 10 to 15% and 16 to 18% near the anode, at the middle and near the cathode respectively. For the test with 12hr polarity reversal, the percentage of moisture content reduction ranges from 11 to 13%, 6 to 14% and 12 to 14% near the anode, at the middle and near the cathode. The percentage of reduction in moisture content in the test with 24hr polarity reversal ranges from 16 to 18%, 16 to 17% and 16 to 19% near the anode, at the middle and near the cathode respectively. The tests with 8hr and 12hr polarity reversal show lowest reduction at the middle of the test bed. Test with 24hr polarity reversal shows a more uniform moisture content reduction throughout the test bed. The test without polarity reversal show highest overall reduction in moisture content. The reduction ranges from 39 to 43%, 29 to 35% and 20 to 28% near the anode, at the middle and near the cathode respectively. The test without polarity reversal show a more non-uniform trend in moisture content with higher reduction near the anode and lower reduction near the cathode.

Table 6.4 shows the final moisture content of peat after EO tests without and with 24hr polarity reversal. In the test without polarity reversal, final moisture content ranges from 430 to 468%, 457 to 477% and 495 to 512% near the anode, at the middle and near the cathode respectively. For the test with 24hr polarity reversal, the final moisture content ranges from 481 to 519%, 556 to 574% and 509 to 547% near the anode, at the middle and near the cathode respectively. As observed in the tests on organic soil, in peat, the test without polarity reversal shows higher final moisture contents near the cathode and lower final moisture contents near the anode. In the test with polarity reversal, highest final moisture contents are observed at the middle of the test bed. This may be due to the change in EO flow direction with each polarity reversal. With each change in flow direction, only a portion of the water is moved to the cathode while a portion remained in the test bed.

Table 6.4 also shows the percentage of moisture content reduction between the test without and with polarity reversal. In the test without polarity reversal, the percentage of moisture content reduction ranges from 27 to 33%, 25 to 29% and 20 to 23% near the anode, at the middle and near the cathode respectively. Lower reduction is observed near the cathode while higher reduction is seen near the anode. For the test with 24hr polarity reversal, the percentage of moisture content reduction ranges from 20 to 26%, 11 to 14% and 16 to 21% near the anode, at the middle and near the cathode respectively. The test without polarity reversal shows highest overall reduction in moisture content. While in the test with 24hr polarity reversal, the middle the test bed, at 12.5cm from the cathode shows the least reduction in moisture content

The tests with polarity reversal in organic soil and peat exhibit lower reduction in moisture content at the middle of the test bed. The constant change in direction of flow during polarity reversal might not have allowed for sufficient time for a portion of the water to be moved to the cathode. This resulted in a portion of the water moving only part of the way toward the cathode, causing accumulation of water at the middle region of the test bed. The lower EO flow and accumulation of water at the centre region during polarity reversal resulted in lower dewatering effects. Similar observation was made by Micic, Shang and Lo, (2001), where the centre of the soil showed lowest reduction in moisture content after test with polarity reversal.

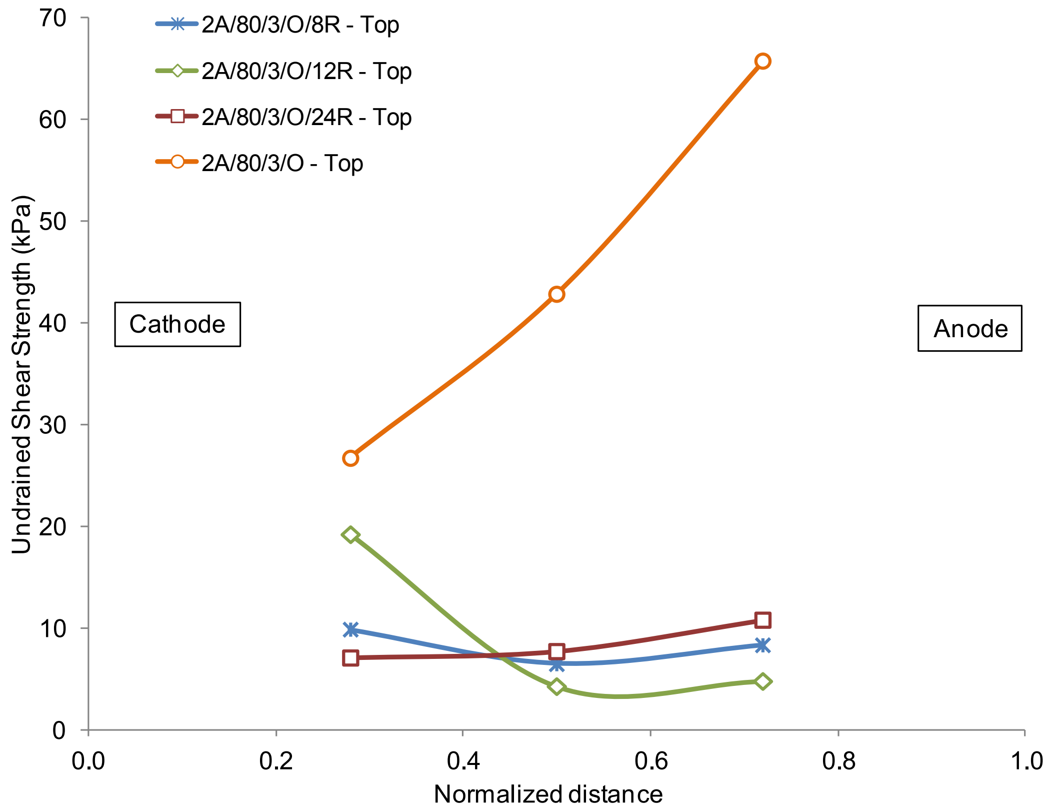
Table 6.3: Comparison of final moisture content post EO tests on organic soil with polarity reversal

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
2A/80/3/O/8R	254	212	227	214	16	10	15	0 - 3 cm
		213	225	205	16	11	19	3 - 6 cm
		208	226	214	18	11	15	6 - 9 cm
		-	216	210	-	15	17	9 - 12 cm
2A/80/3/O/12R	249	219	234	221	12	6	11	0 - 3 cm
		215	227	215	13	9	13	3 - 6 cm
		213	219	218	14	12	12	6 - 9 cm
		-	213	246	-	14	1	9 - 12 cm
2A/80/3/O/24R	254	213	212	213	16	16	16	0 - 3 cm
		205	212	211	19	16	17	3 - 6 cm
		206	210	213	19	17	16	6 - 9 cm
		-	-	207	-	-	18	9 – 12 cm
2A/80/3/O	221	176	157	129	20	29	42	0 – 4.5 cm
(No reversal)		170	148	129	23	33	42	4.5 - 9 cm
		162	144	126	27	35	43	9 – 13.5 cm
		160	144	134	28	35	39	13.5 - 17 cm

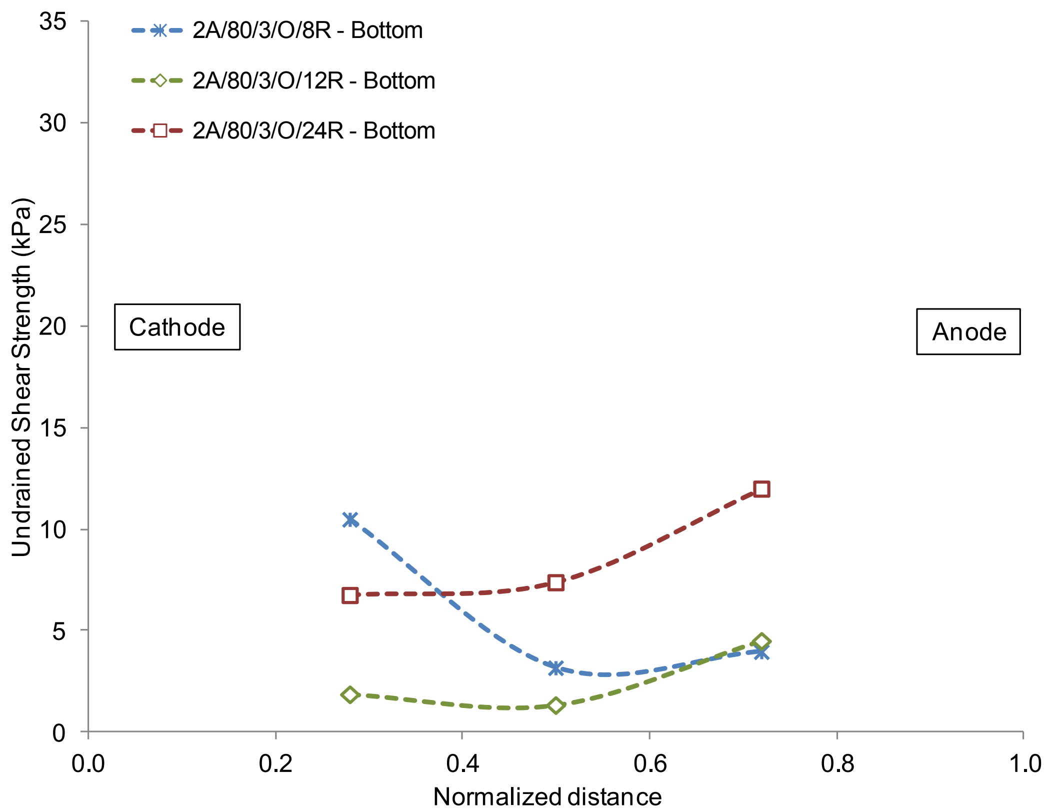
Table 6.4: Comparison of final moisture content post EO tests on peat with and without polarity reversal

Test	Initial moisture content (%)	Final moisture content (%)			Percentage reduction (%)			Height of soil from bottom of tank
		7cm from cathode	12.5cm from cathode	18cm from cathode	7cm from cathode	12.5cm from cathode	18cm from cathode	
2A/40/3/S/NR	641	501	457	430	22	29	33	0 - 3 cm
		499	465	445	22	27	30	3 - 6 cm
		495	477	459	23	25	28	6 - 9 cm
		512	475	468	20	26	27	9 - 12 cm
2A/40/3/S/24R	650	509	558	481	21	14	26	0 - 3 cm
		547	574	511	16	11	21	3 - 6 cm
		523	556	519	19	14	20	6 - 9 cm
		-	-	511	-	-	21	9 - 12 cm

6.3.4 Undrained shear strength after EO tests on organic soil and peat



(a)



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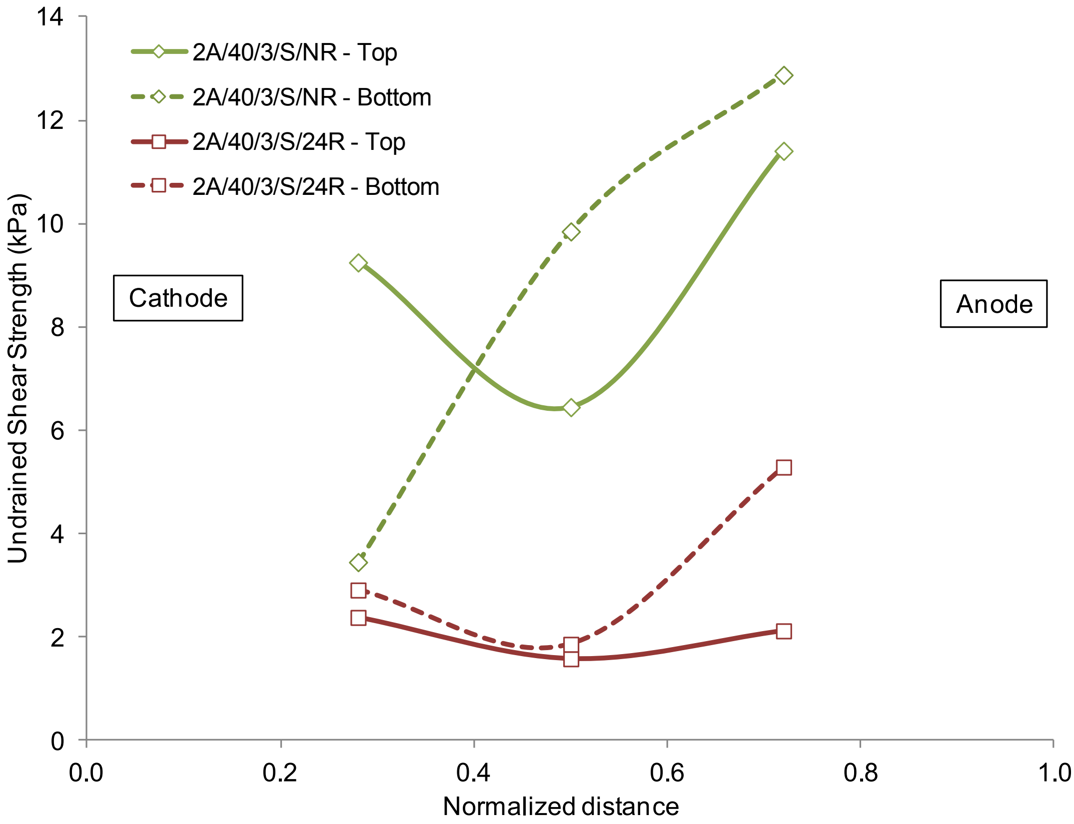

(c)

Figure 6.8: Undrained shear strength at (a) top and (b) bottom of organic soil; and (c) top and bottom of peat after EO tests with polarity reversal

Laboratory vane shear tests were carried out at 0.28, 0.5 and 0.72 normalized distances from the cathode at the top and bottom of the test bed. Figure 6.8 shows the variation in final undrained shear strength of organic soil and peat after EO tests with polarity reversal. The initial shear strengths of the organic soil and peat were less than 2kPa.

Figure 6.8(a) shows the final undrained shear strength at the top of the organic soil. Data from previous test without polarity reversal is also included. In the test with 8hr polarity reversal, final undrained shear strength ranges from 6.5 to 9.8kPa. For the test with 12hr polarity reversal, final undrained shear strength ranges from 4.2 to 19.2kPa. In the test with 24hr polarity reversal, final undrained shear strength ranges from 7.1 to 10.8kPa. Final undrained shear strength for the test without polarity reversal ranges from 26.7 to 65.8kPa. Tests with polarity reversal show significantly lower undrained shear strengths compared to that of the test without polarity reversal. However, the tests with polarity reversal show more uniform strength gain between the electrodes.

Figure 6.8(b) shows the final undrained shear strength at the bottom of the organic soil. In the test with 8hr polarity reversal, final undrained shear strength ranges from 3.2 to 10.5kPa. In the test with 12hr polarity reversal, final undrained shear strength ranges from 1.3 to 4.5kPa. For the test with 24hr polarity reversal, final undrained shear strength ranges from 6.7 to 12.0kPa. The final undrained shear strengths at the bottom of the organic soil also show a more uniform trend.

Figure 6.8(c) shows the variation in final undrained shear strength at top and bottom of the peat. In the test without polarity reversal, final undrained shear strength at the top ranges from 6.4 to 11.4kPa. At the bottom of the peat, final undrained shear strength ranges from 3.4 to 12.9kPa. For the test with polarity reversal, final undrained shear strength at the top ranges from 1.6 to 2.4kPa. At the bottom of the peat, final undrained shear strength ranges from 1.9 to 5.3kPa. Higher strength gain is observed in the test without polarity reversal, which is also seen the tests on organic soil. The trend of final undrained shear strengths is reflected in the moisture content reduction of the same test. No significant improvement is seen in the undrained shear strength of the test with polarity reversal as initial shear strength was 1.06kPa. Although the final undrained shear strengths in the test with polarity reversal show lower variation, the overall improvement in shear strength is less than desirable.

6.4 Chapter Summary

This chapter presented the observations and findings of the small scale test series carried out to determine a pumping interval for the drainage well in EO consolidation tests on organic soil and peat. Tests with polarity reversal were also carried out to evaluate the uniformity of improvement in organic soil and peat. Findings from the test series detailed in this chapter are listed below:

6.4.1 Pumping interval in EO consolidation of organic soil and peat

EO tests with pumping intervals of 3hr, 6hr and 24hr of the drainage well were carried out in organic. For peat, the pumping intervals were 3hr and 6hr. Applied voltage gradient was 80V/m. Control tests for organic soil and peat without application of DC and pumping intervals of 12hr were included.

The control test on organic soil and peat show the lowest settlement. Application of DC expedited settlement in organic soil and peat. Tests with 3hr pumping interval show the highest settlement. The higher settlement observed in the tests with 3hr pumping interval is attributed to the frequent removal of water collected in the drainage well. This might reduce the counteracting hydraulic gradient build up near the cathode and reduce the disruption in EO flow toward the cathode. This is in agreement with the highest volume of water collected in the tests with 3hr pumping interval. With higher volume of water removed, settlement is also higher.

Lower reduction in moisture content is observed in the control tests on organic soil and peat. Tests with 3hr pumping interval on organic soil and peat show the highest reduction in moisture content. Maximum reduction in moisture content is 43% and 34% for organic soil and peat respectively. All the EO tests on organic soil and peat show higher reduction in moisture content near the anode and lower reduction in moisture content near the cathode. This reflected the direction of EO flow from anode toward the cathode.

The shear strength of the control tests shows no significant improvement. Application of DC greatly improved the shear strength of organic soil and peat. Highest strength gain is observed in the test with 3hr pumping interval with maximum of 66kPa and 23kPa in organic soil and peat respectively. This translates to 1860% and 2024% improvement in organic soil and peat respectively. The final undrained shear strength of organic soil and peat show higher improvement near the anode and lower improvement near the cathode.

6.4.2 Polarity reversal in EO consolidation of organic soil and peat

Polarity reversal was carried out during EO consolidation of organic soil and peat. Polarity reversal intervals adopted were 8hr, 12hr and 24hr for organic soil and 24hr for peat. In organic soil voltage gradient applied was 80V/m and in peat, voltage gradient applied was 40V/m. Tests without polarity reversal were also included.

In organic soil, the difference in settlement near the anode and cathode is 4.1% for test without polarity reversal. With polarity reversal, the difference in settlement is 0.1%, 0.7% and 2.3% for tests with 8hr, 12hr and 24hr reversal intervals. Highest uniformity in settlement between the anode and cathode is observed in the test with 8hr polarity reversal. However the overall settlement of the test with 8hr polarity reversal shows the lowest magnitudes. For peat, test with polarity reversal show a difference in settlement near the anode and cathode of 0.8%. However the maximum settlement of the test with 24hr polarity reversal is 1.45 times lower than that of the test without polarity reversal. Tests with polarity reversal on organic soil and peat resulted in less variation in settlement between the anode and cathode. At the same time, the settlement of the tests with polarity reversal show significantly lower magnitudes compared to that of the tests without polarity reversal.

Higher volume of water is collected in the tests without polarity reversal. In organic soil, the volume of water collected is 1.8 times higher than that in tests with polarity reversal. For peat, the volume of water collected in the test without polarity reversal is twice of that collected in the test with polarity reversal. EO flow in peat during test with polarity reversal was greatly reduced.

With the low total volume of water collected in the tests with polarity reversal, the reduction in moisture content of the organic soil and peat is also low. The tests without polarity reversal show highest reduction in moisture content near the anode and lowest reduction near the cathode. In organic soil, tests with 8hr and 12hr polarity reversal show higher reduction near the electrodes while lower reduction is observed in the middle of the test bed. The test on organic soil with 24-hour polarity reversal shows the highest degree of uniformity in reduction of moisture content with reduction ranging between 16 to 19% throughout the test bed. In peat, with 24hr polarity reversal, a more uniform reduction in moisture content is observed near the electrodes. The middle of the test peat show lower moisture content reduction, a similar trend observed in tests with 8hr and 12hr polarity reversal on organic soil. The trend of lower reduction in moisture content at the middle between the electrodes implies that the constant change in direction of EO flow during polarity reversal caused a portion of the water to accumulate at the middle of the test bed.

With the lower settlement and moisture content reduction in tests with polarity reversal, the improvement in shear strength is also low. In organic soil, test without polarity reversal shows final undrained shear strength with magnitudes above 20kPa. In the tests with polarity reversal, the final undrained shear strengths have magnitudes below 20kPa. For peat, the maximum final undrained shear strength is

13kPa in the test without polarity reversal. In the test with 24hr polarity reversal, the maximum undrained shear strength is low at 5kPa. In spite of the low improvement in shear strength, a more uniform trend in strength gain is observed in the tests with polarity reversal.

7 Conclusion and Further Studies

7.1 Introduction

This study aims to investigate the effects of electro-osmosis on the consolidation of peat and organic soils. The objectives of this study are to evaluate the effects of voltage gradient, electrode configuration, pumping interval of the drainage well and polarity reversal on the electro-osmosis consolidation.

7.1.1 Effect of voltage gradient during EO on consolidation of peat and organic soil

In the small scale 1anode-1cathode EO test in peat, the test with voltage gradient of 100V/m resulted in the largest settlement, highest volume of water collected, reduction in moisture content and increment in shear strength. Voltage gradient of 120V/m showed no significant improvement in settlement of peat over voltage gradient of 100V/m. The large scale test with a grid electrode configuration at voltage gradient of 80V/m showed the largest overall settlement compared to tests with voltage gradients of 100V/m and 120V/m. In the square, R4, electrode configuration test, the highest overall settlement is observed in the test with 100V/m. For the hexagon, R6, electrode configuration tests, the largest settlement and highest volume of water collected is observed in the test with voltage gradient of 100V/m. With the increase in voltage gradient from 80V/m to 100V/m during EO test on peat, the magnitude of settlement, volume of water collected and strength gain also show increase. However higher voltage gradient of 120V/m did not result in significant increment in settlement, volume of water collected and strength gain of peat. All the EO tests on peat show a possibility of an optimum voltage gradient where settlement is of the largest magnitude. All except one test exhibit the possible optimum voltage gradient in the region of 100V/m. The large scale grid electrode configuration test shows a possible optimum voltage gradient of 80V/m.

In the incremental voltage gradient tests, the maximum settlement of organic soil and peat is 1% and 2% respectively lower than the tests with fixed 80V/m. The total volume of water collected in the tests with incremental voltage is lower than the tests with fixed 80V/m. The improvement in shear strength of the organic soil and peat in the incremental voltage gradient tests is lower than the fixed voltage gradient. The overall lower settlement, total volume of water collected and gain in shear strength might be due to the lower average voltage gradient of 45V/m in the incremental voltage tests in comparison to the fixed 80V/m in the fixed voltage tests. For the EO tests with incremental voltage gradient, the initial voltage should be a minimum of 30V/m. Voltage gradient less than 30V/m resulted in EO flow that did not show significant increment over the flow of the control tests.

Fixed applied current during EO tests is a variation of voltage gradient, where constant current is maintained through soil medium. Tests with constant currents on organic soil show that EO flow is proportional to the current transmitted through the soil. Higher constant current of 20mA resulted in 3% higher settlement than constant current of 10mA. Total volume of water collected in the constant 20mA test is 15% higher than the constant 10mA test. Maximum reduction in moisture content of 35% is recorded in the constant 20mA test. Maximum shear strength improvement of the constant 20mA test is double the maximum shear strength of the constant 10mA test. Increase in applied current on organic soil results in increase of settlement, volume of water collected and strength gain. However, in EO flow in test with constant current of 20mA exhibited gradual reduction throughout the test. This reduction in EO flow is not observed in the constant 10mA test.

7.1.2 Effect of radial electrode configuration on EO of peat

In the radial electrode configuration tests with 80V/m for test duration of 8 days, the square, R4, electrode configuration showed the highest overall average normalized settlement. In the test with 100V/m with test duration of 16 days, the hexagon, R6, electrode configuration showed a 0.6% higher overall average normalized settlement. With voltage gradient of 120V/m and test duration of 12 days, R4 electrode configuration showed marginally higher overall average normalized settlement by 0.4%.

The total volume of water collected is highest in the R4 electrode configuration at 80V/m. While at 100V/m, the R6 electrode configuration showed the highest total volume of water collected. At voltage gradient of 120V/m, the total volume of water collected in the R4 electrode configuration test was marginally higher than the R6 electrode configuration test. This is in agreement with the highest overall average normalized settlement observed in each respective test series. All R4 and R6 electrode configuration tests showed higher moisture content reduction at the top of the test bed. Higher moisture content reduction is also observed near the anodes compared to the central cathode.

The final undrained shear strength of the tests with radial electrode configurations also reflects the settlement and volume of water removed. In the 80V/m test, the R4 electrode configuration showed higher strength gain. For the 100V/m test, higher final undrained shear strength is observed in the R6 electrode configuration test. At 120V/m, R4 electrode configuration test showed higher final undrained shear strength.

The overall average settlement of the R4 and R6 electrode configuration tests showed marginal difference. With higher number of anodes in the R6 electrode configuration, the effective electric field during EO is higher than the R4 electrode configuration. It was expected that the settlement of the R6 electrode configuration test would be higher. However, settlement results of the R6 electrode configuration tests did not show significant higher settlement over the R4 electrode configuration tests. Similar observation is also seen in the total volume of water collected and improvement in strength of the R6 electrode configuration.

7.1.3 Effect of pumping interval of drainage well during EO of organic soil and peat

The settlement is largest in the 3hr pumping interval for both the organic soil and peat. The maximum settlement is 11% for pumping interval of 3hr in organic soil. In peat, the maximum settlement is 25% 3hr pumping interval. Highest total volume of water collected is observed in the test with 3hr pumping interval in the EO tests on organic soil and peat. Maximum moisture content reduction of organic soil and peat is 43% and 34% respectively. The final undrained shear strength of the organic soil and peat of the 3hr pumping interval EO tests is the highest. The EO tests with the shortest pumping interval of 3hr resulted in largest settlement, highest total volume of water collected and highest final undrained shear strength in organic soil and peat.

7.1.4 Effect of polarity reversal during EO tests in organic soil and peat

In the tests with polarity reversal on organic soil and peat, the difference in settlement near the anode and cathode is 0.1% and 0.8% respectively. While without polarity reversal, the differential settlement is higher at 4.1% and 4% respectively for organic soil and peat. A more uniform settlement near the anode and cathode is achieved with polarity reversal during EO test.

Although the settlement is more uniform in EO tests with polarity reversal, the magnitude of settlement is lower than that of tests without polarity reversal in both organic soil and peat. The total volume of water collected in the respective polarity reversal tests on organic soil and peat is 1.8 and 2.0 times lower than the tests without polarity reversal. In the polarity reversal test on organic soil, the reduction in moisture content also showed more uniform reduction throughout the test bed. While in peat, polarity reversal resulted in lower reduction in moisture content at the middle of the test bed.

The lower total volume of water collected in the EO tests with polarity reversal is reflected in the lower improvement in shear strength. In organic soil, the final undrained shear strengths are lower than 20kPa in the polarity reversal test while the final undrained shear strengths are higher than 20kPa in the test without polarity reversal. For peat, the maximum final undrained shear strength is 5kPa in the test with polarity reversal, which is marginally higher than the initial shear strength. Test without polarity reversal resulted in higher maximum final undrained shear strength of 13kPa in peat.

Polarity reversal in organic soil might be applicable if a higher degree of uniformity is desired while the required magnitude of settlement and strength gain is minimal. Polarity reversal of 24hr intervals might not be suitable in peat as the resulting magnitude of settlement and strength gain is low.

7.2 Future studies

This study was conducted using parameters of voltage gradient, radial electrode configuration, pumping interval and polarity reversal. Experimental works on these parameters have not been carried out in peat and organic soil before. Hence this study mainly concentrated on the improvement of peat and organic soil after electro-osmosis treatment in terms of settlement, water content reduction and strength gain.

The experimental works in this study provides a basis for future studies on electro-osmosis treatment of peat and organic soil.

This study is limited to the bounds of the laboratory. A field test was not carried out due to limitations in availability of a suitable site as well as funds required for a field test. The plan area of electro-osmosis treatment should be comparable to the depth of peat or organic soil. Chew *et al.* (2004) did not observed any settlement in their field test since the electro-osmotic treatment plan area was small compared to the depth of marine clay treated. If the depth of peat to be treated is 15m, the field test area should be at least 15mx15m in order to obtain meaningful results. With comparatively large test area, the installation and running costs would be relatively high.

Future field studies in peat and organic soil would further substantiate results of the current laboratory study. The occurrence of cracks in the peat of the small scale tests at higher voltage gradient of 120V/m is not observed in the large scale tests with the same voltage gradient. Hence the development of cracks at higher voltage gradient of 120V/m can be verified under full-scale field tests. A field trial in peat would verify the possible occurrence of optimum voltage gradient during EO of peat. Further study of the radial electrode configuration can also be carried out under field conditions. With a field study, the cost of implementation of EO consolidation technique can be assessed. However, proper planning incorporating factors such as suitable location, manpower and machinery required, source of direct current as well as necessary safety measures should be carried out before any field test can be done.

The study of EO consolidation with mechanical loading (surcharge/preload) can also be carried out. As surcharging is a more commonly preferred method for ground treatment, the addition of EO treatment during surcharging might result in a reduction in the lengthy treatment period of surcharging."

As the main concern of EO consolidation is the ground settlement, numerical studies can be carried out to predict settlement during EO of peat. Recently, Hu and Wu (2014) have carried out numerical simulation of electro-osmotic consolidation on clay with 1D and 2D electrode configurations. Factors governing EO consolidation included applied voltage gradient and the electrode configuration.

Peat is a more complex material compared to soft clay although both peat and clay exhibit low shear strength and high compressibility. It is found that the Cam-clay model does not adequately capture the complex behaviour of peat. Currently, the constitutive model for peat is still being developed (Zhang and O'Kelly, 2014). Extensive work is expected to formulate a constitutive model capturing electro-osmosis treatment in peat. Numerical simulation of electro-osmotic consolidation of peat can only be conducted when the constitutive model is available.

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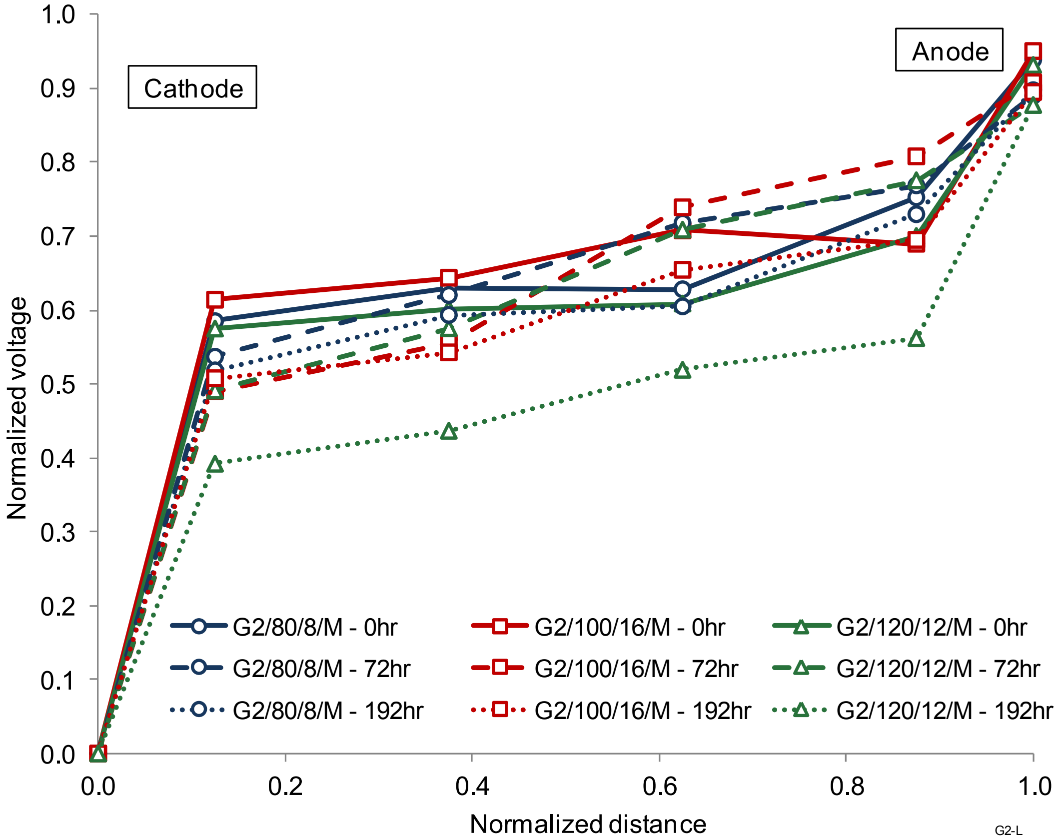
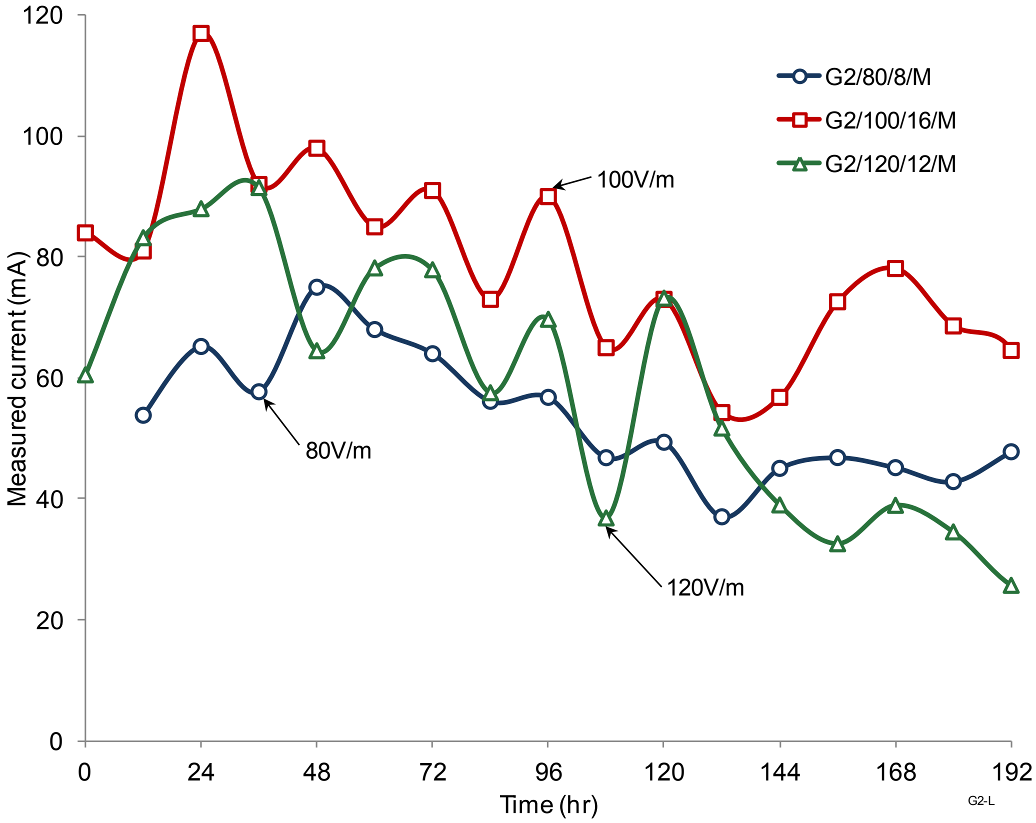
APPENDICES

APPENDIX A

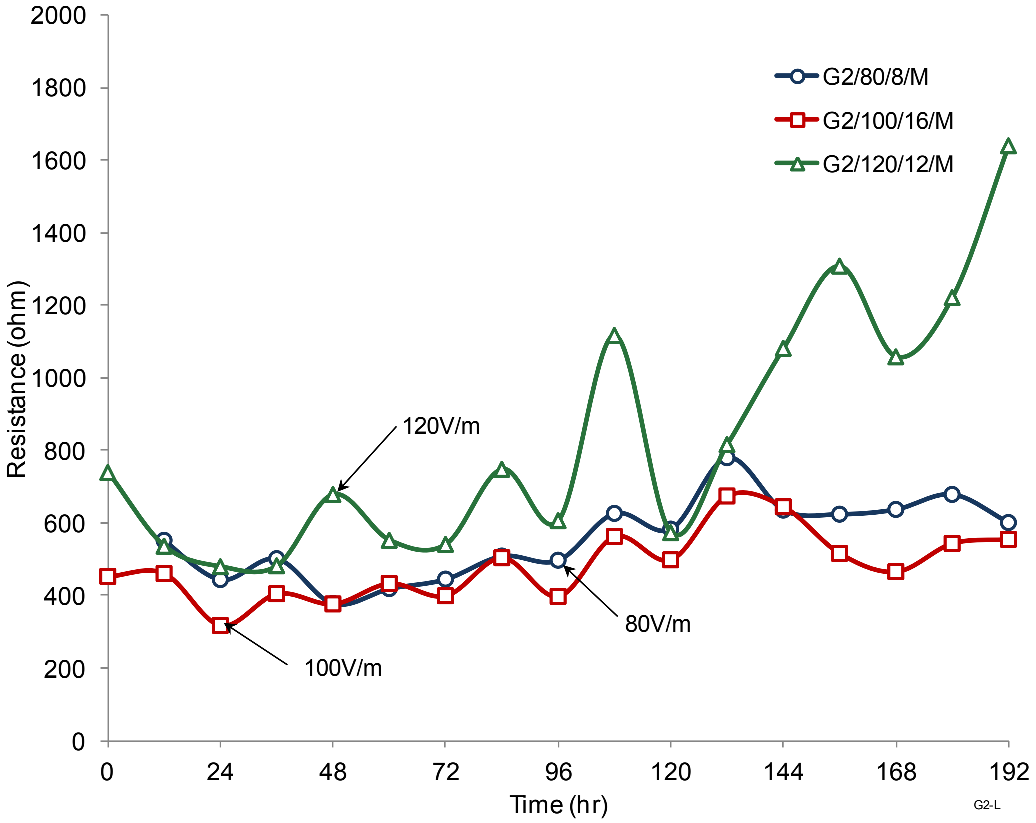
A 1: Variation in voltage with time in peat during EO test, grid electrode configuration, section across L1-L4



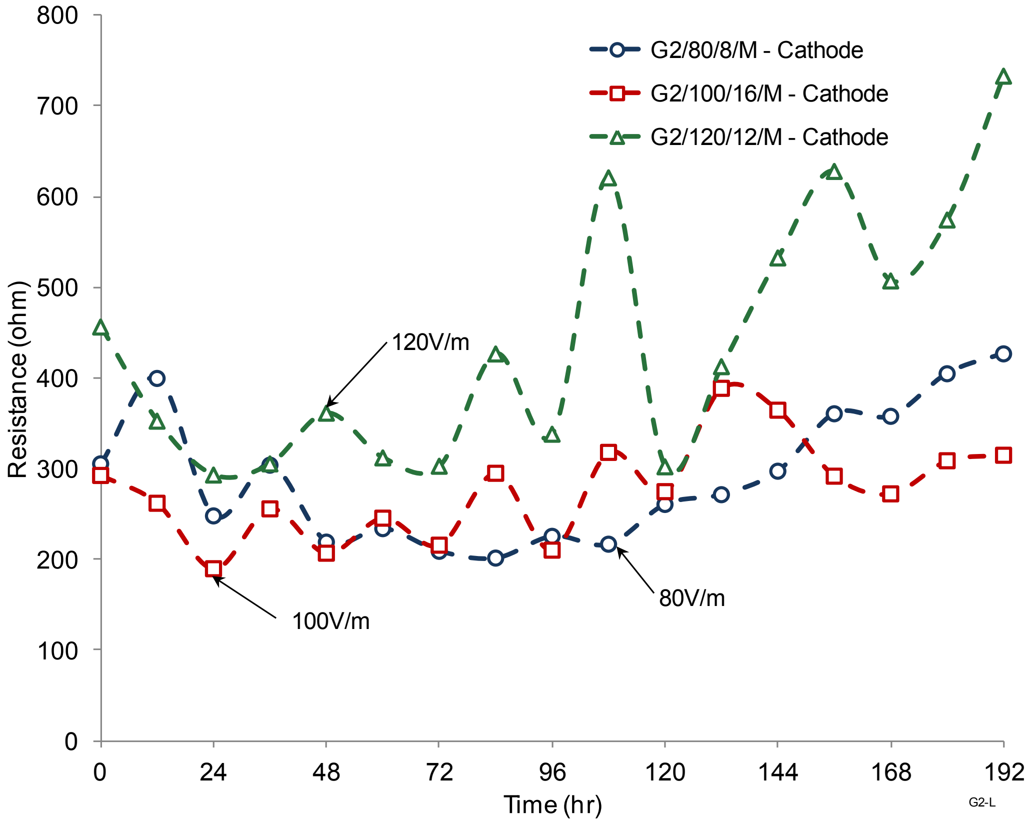
A 2: Variation in measured current with time in peat during EO test, grid electrode configuration, section across L1-L4



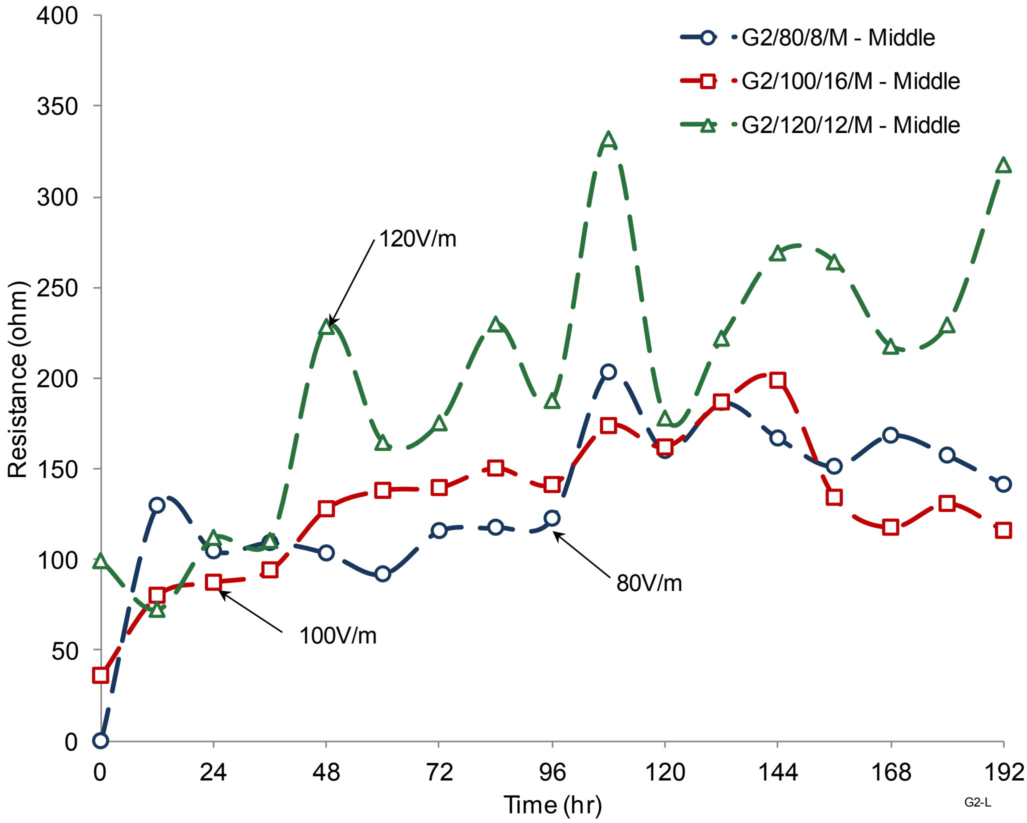
A 3: Overall resistance with time in peat during EO test, grid electrode configuration, section across L1-L4



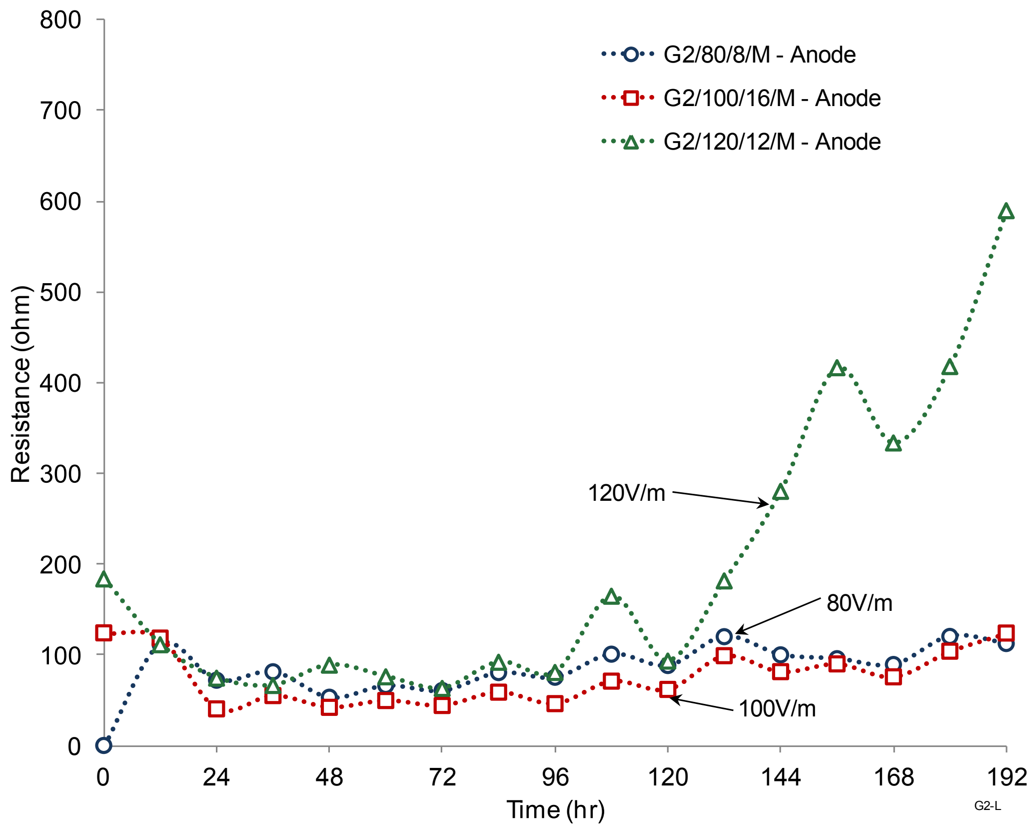
A 4: Variation in resistance with time at cathode region during EO test, grid electrode configuration, across section L1-L4



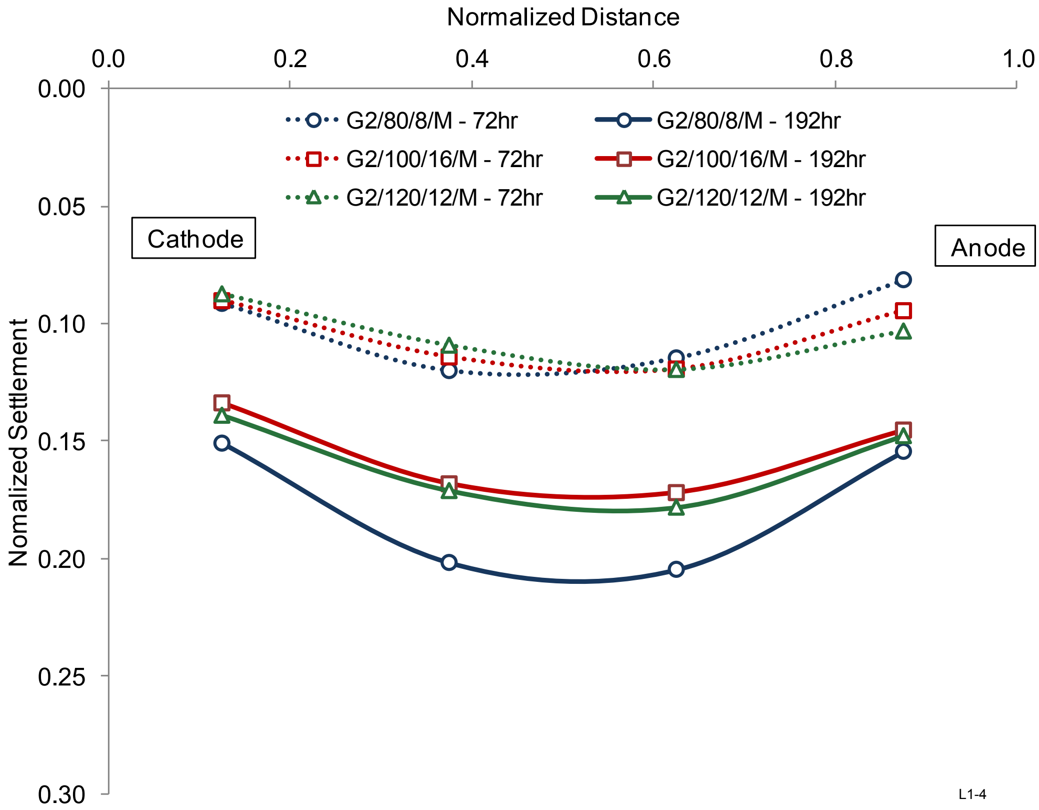
A 5: Variation in resistance with time at middle region during EO test, grid electrode configuration, across section L1-L4



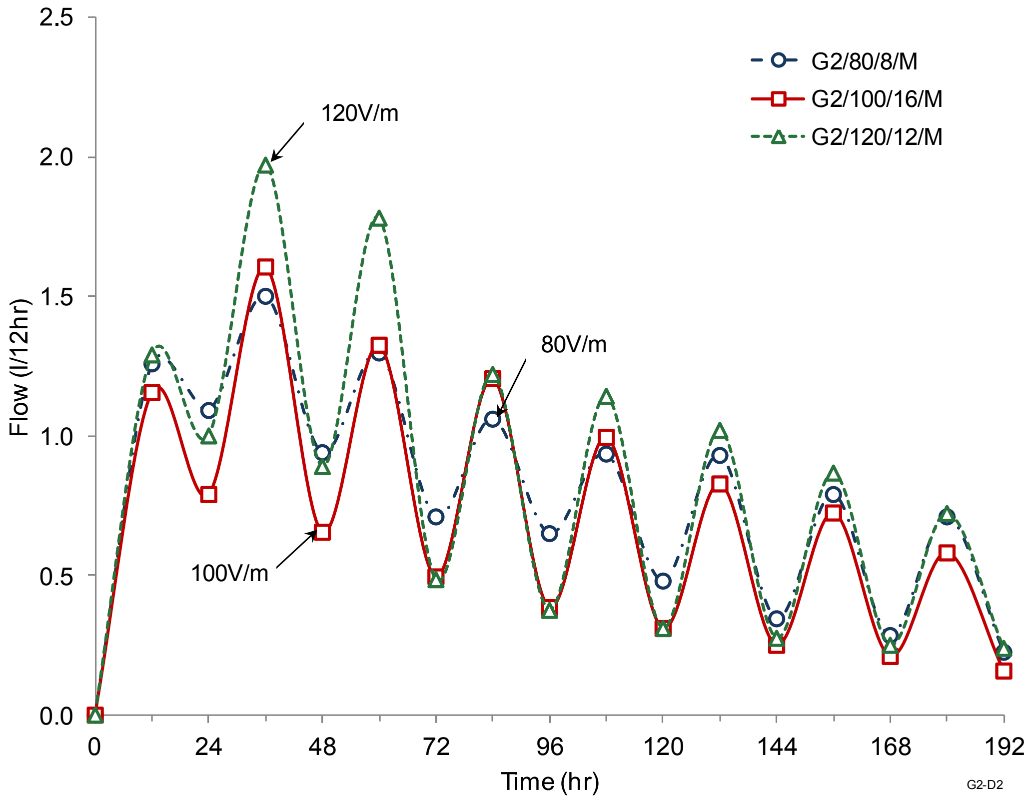
A 6: Variation in resistance with time at anode region during EO test, grid electrode configuration, across L1-L4



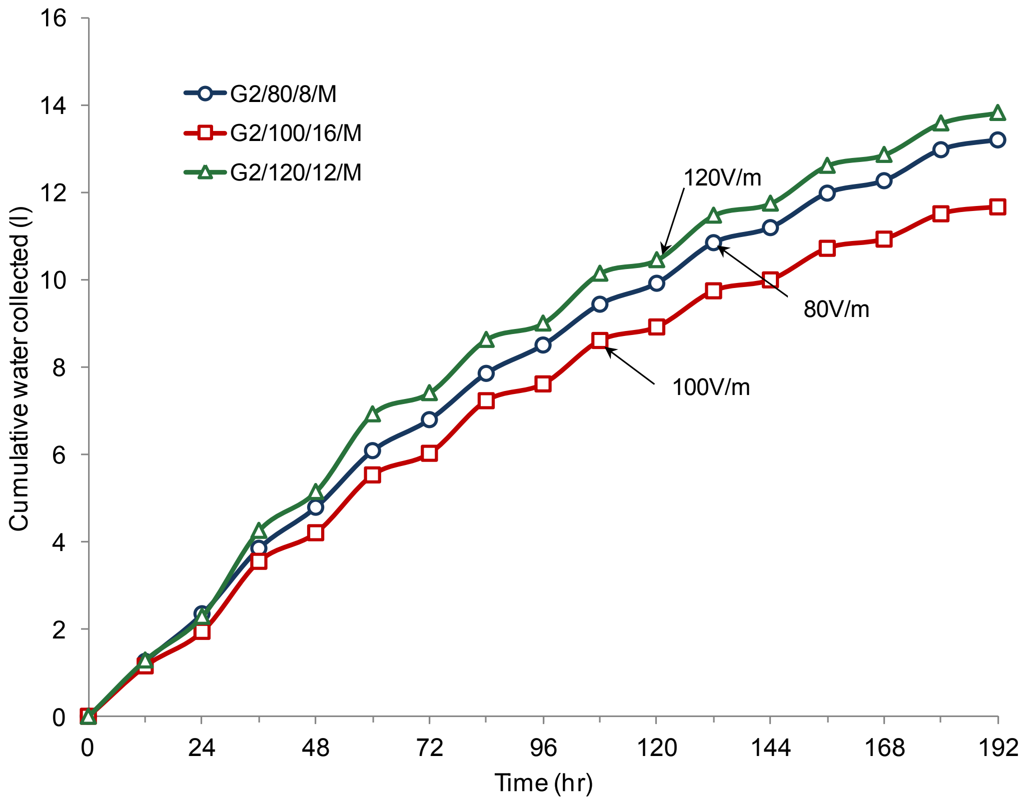
A 7: Variation in normalized surface settlement of peat during EO test, grid electrode configuration, across section L1-L4



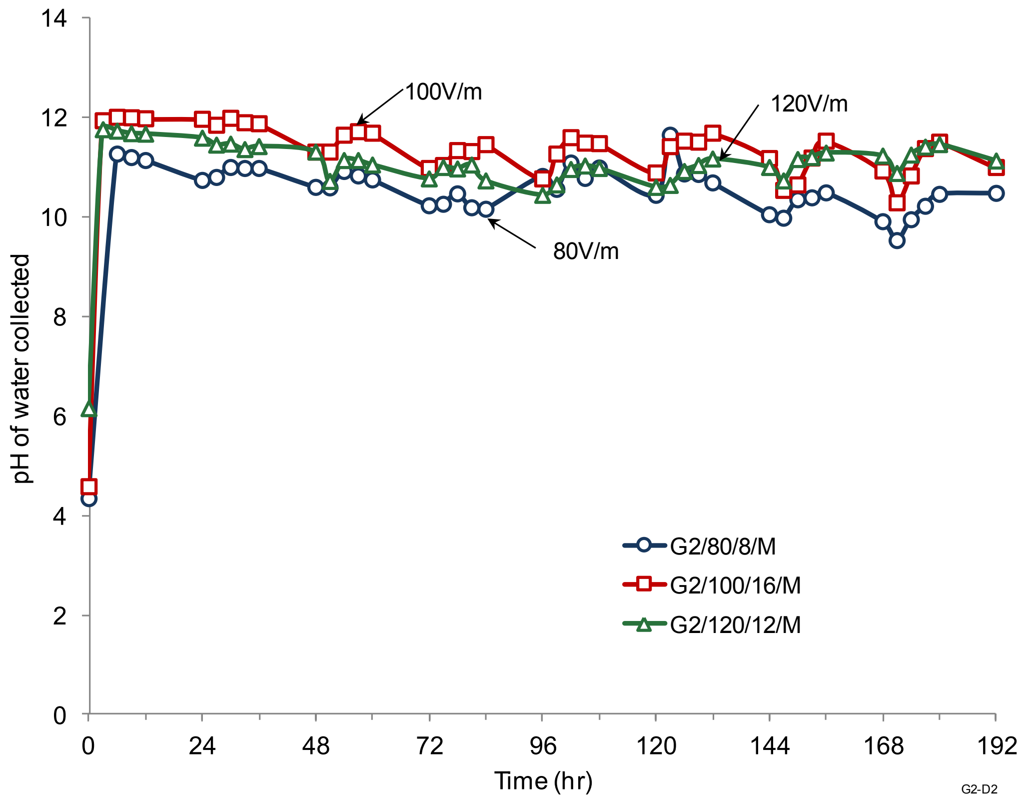
A 8: Variation in flow rate of drain along Grid L in EO test on peat in large scale test with grid electrode configuration



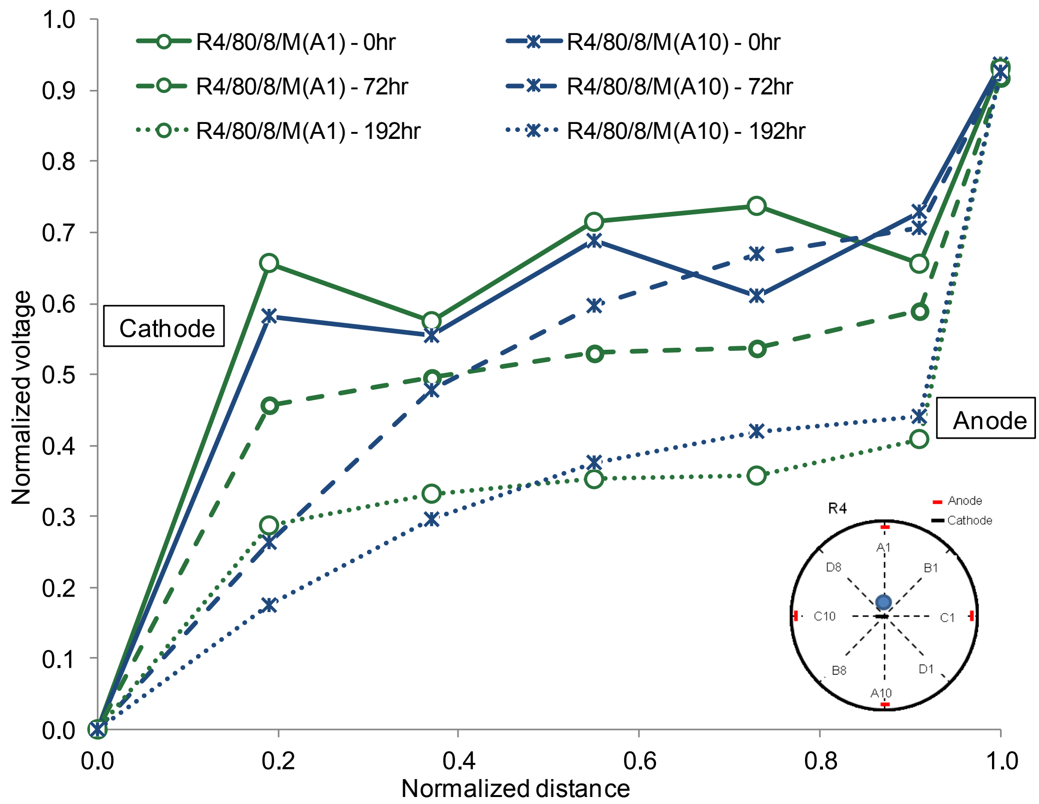
A 9: Cumulative water collected in drain along Grid L in EO test on peat in large scale test with grid electrode configuration



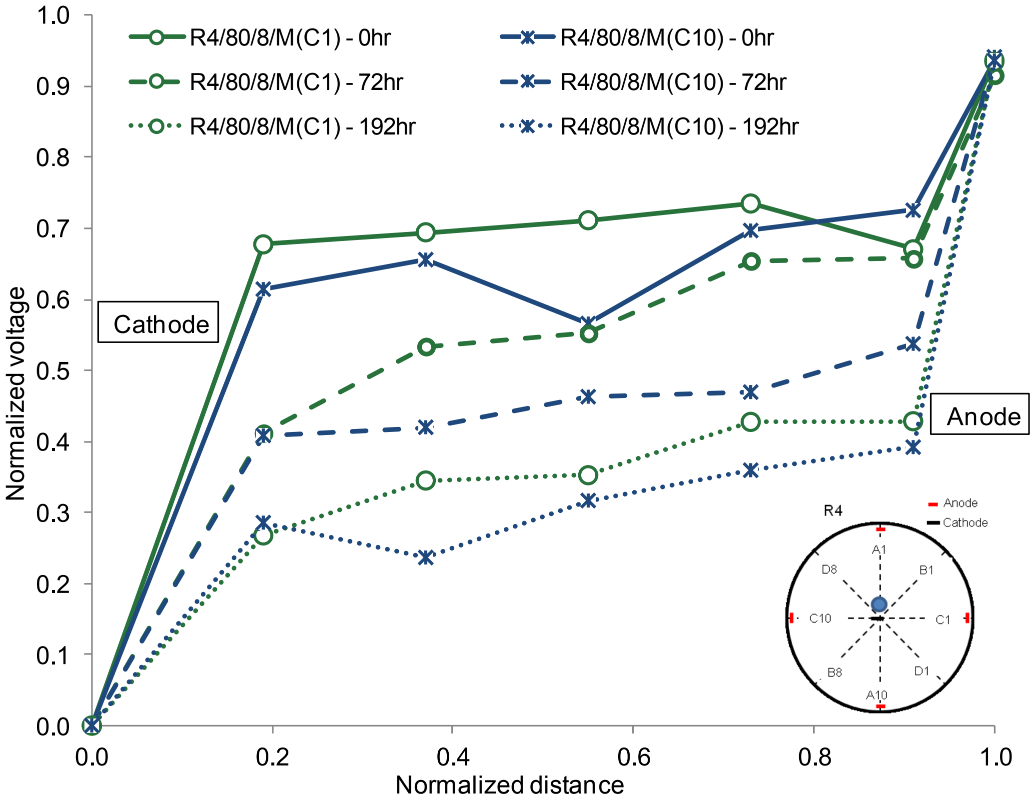
A 10: Variation in pH of water collected from drain along Grid L in EO tests on peat in large scale test with grid electrode configuration



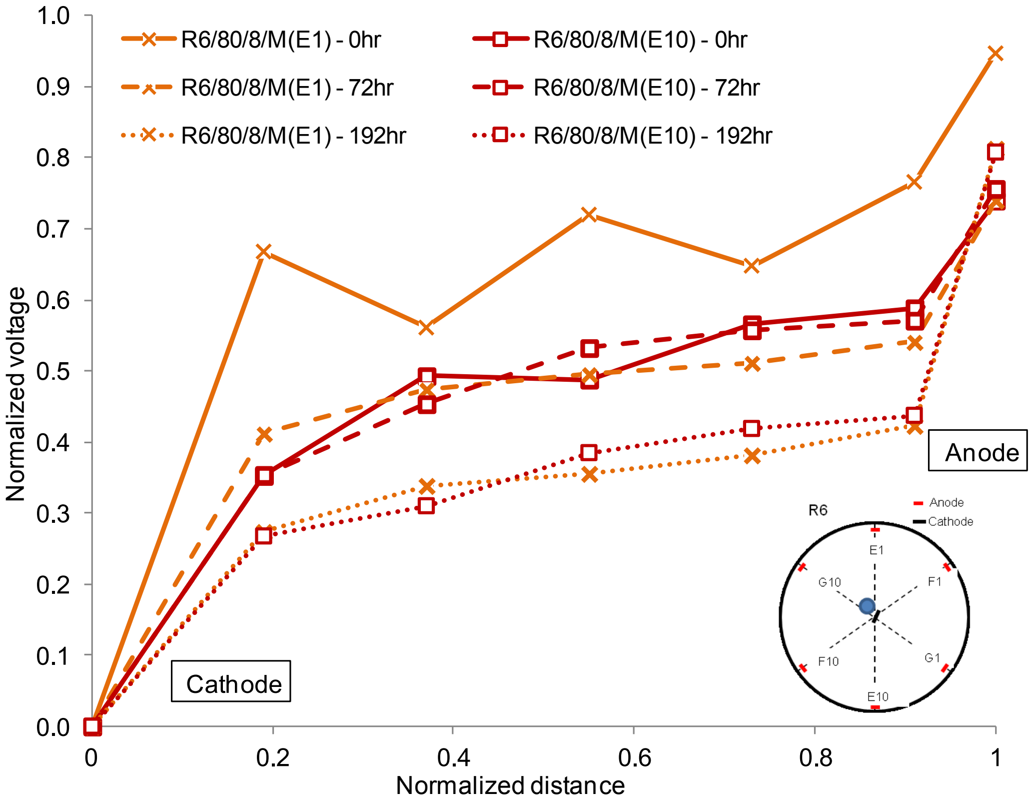
A 11: Variation in measured voltage with time along Grid A in EO tests on peat with R4 electrode configuration at 80V/m



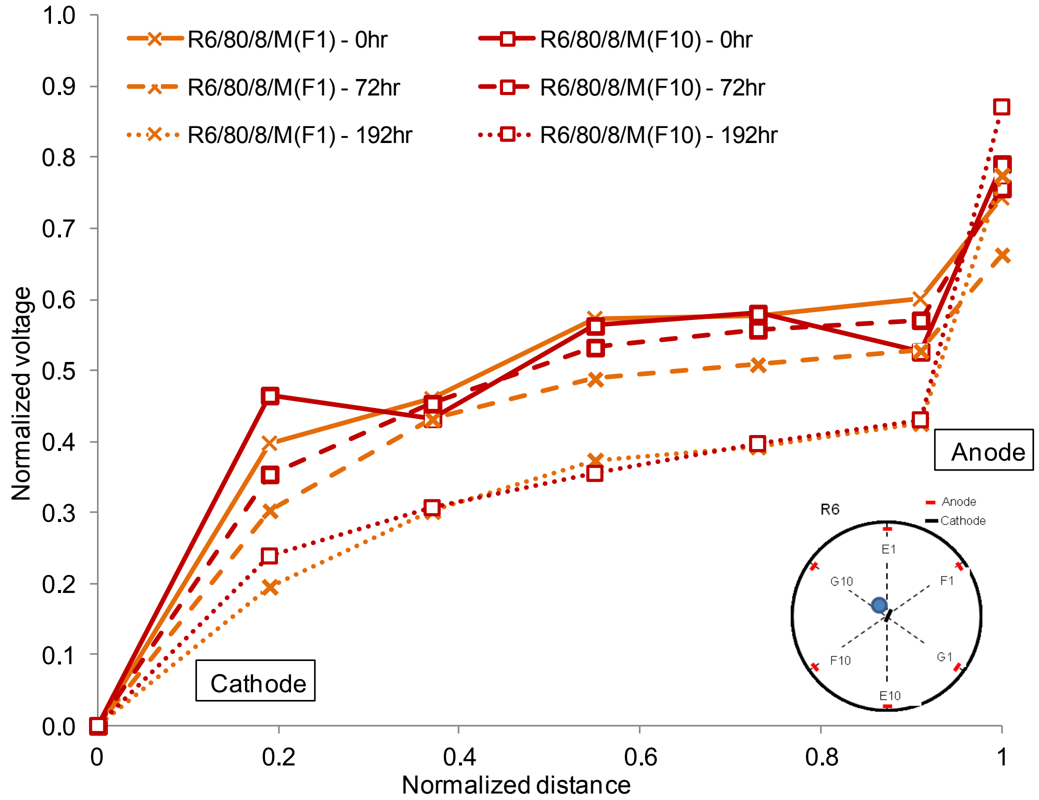
A 12: Variation in measured voltage with time along Grid C in EO tests on peat with R4 electrode configuration at 80V/m



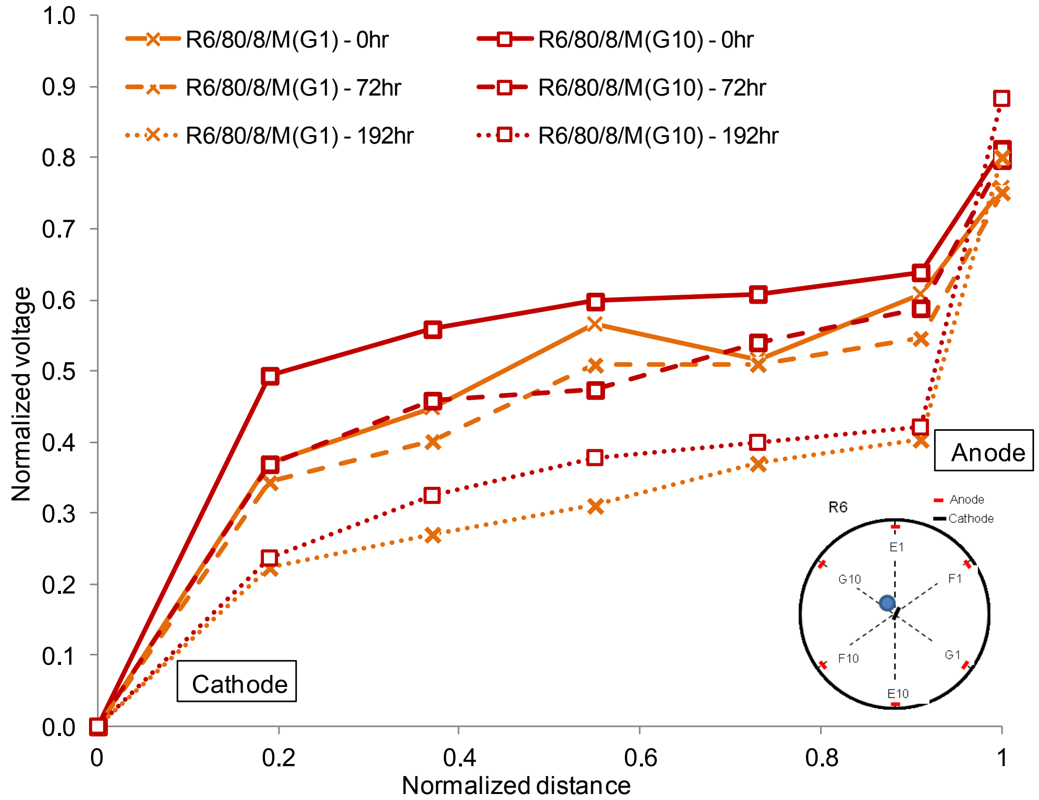
A 13: Variation in measured voltage with time along Grid E in EO consolidation of peat in test with R6 electrode configuration at 80V/m



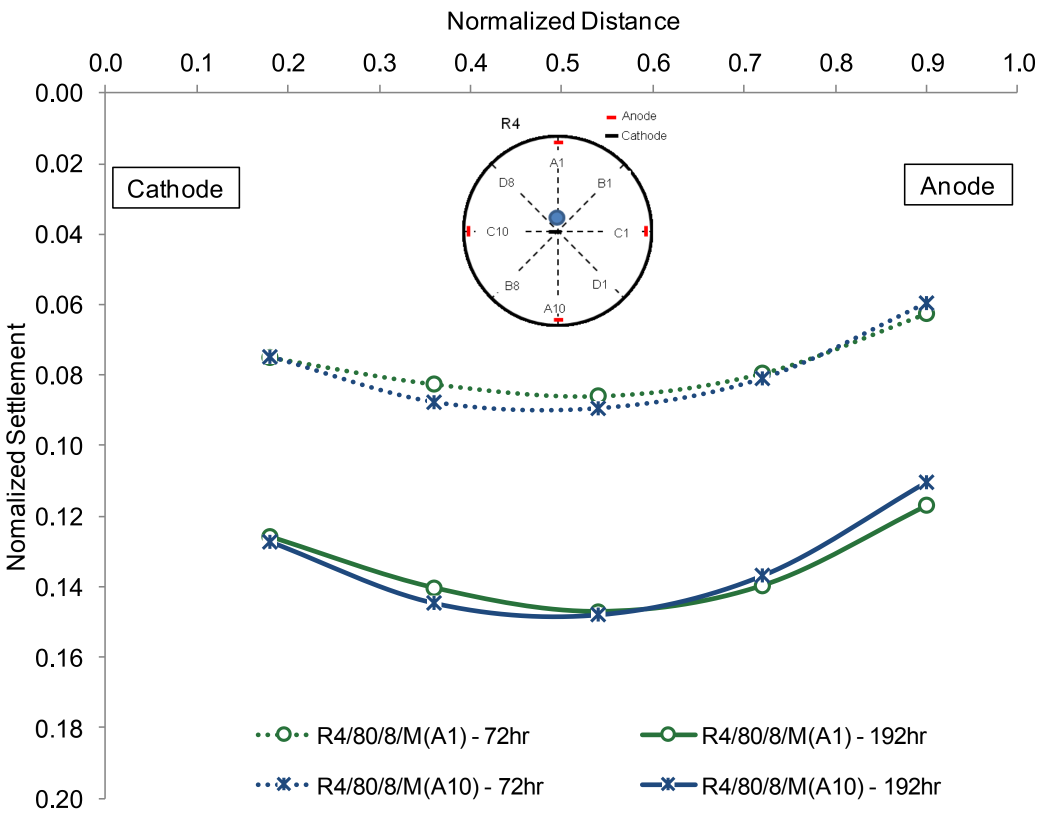
A 14: Variation in measured voltage with time along Grid F in EO consolidation of peat in test with R6 electrode configuration at 80V/m



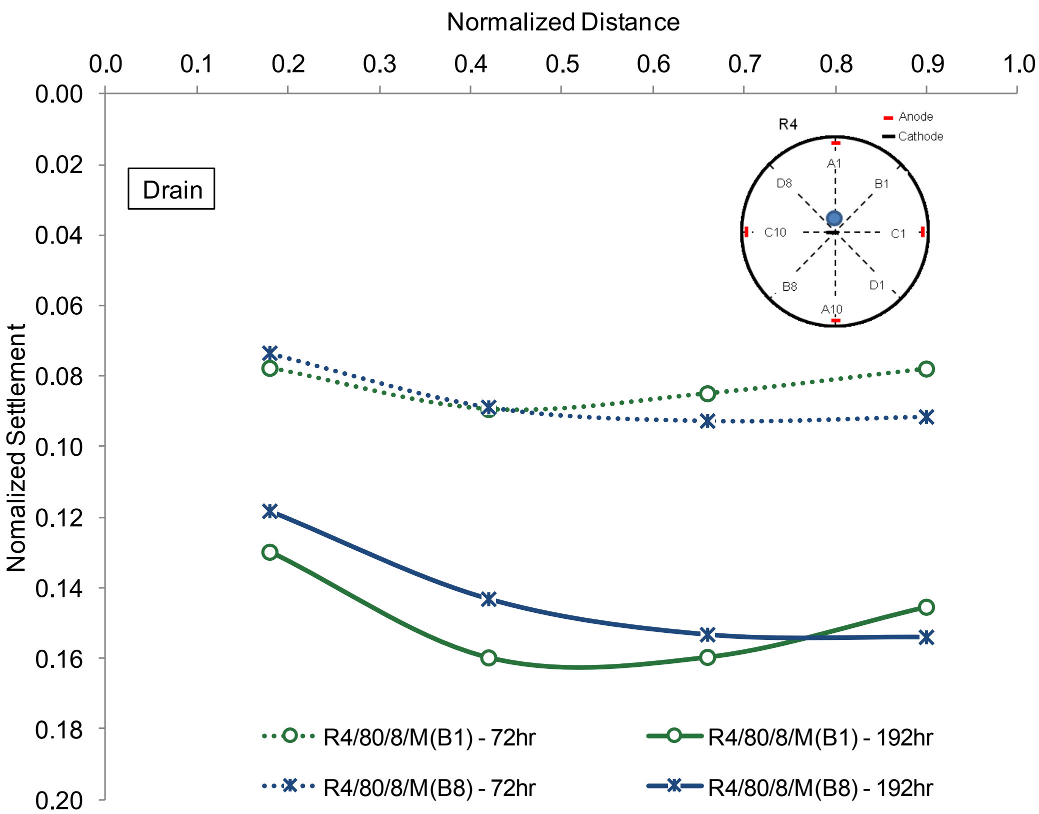
A 15: Variation in measured voltage with time along Grid G in EO consolidation of peat in test with R6 electrode configuration at 80V/m



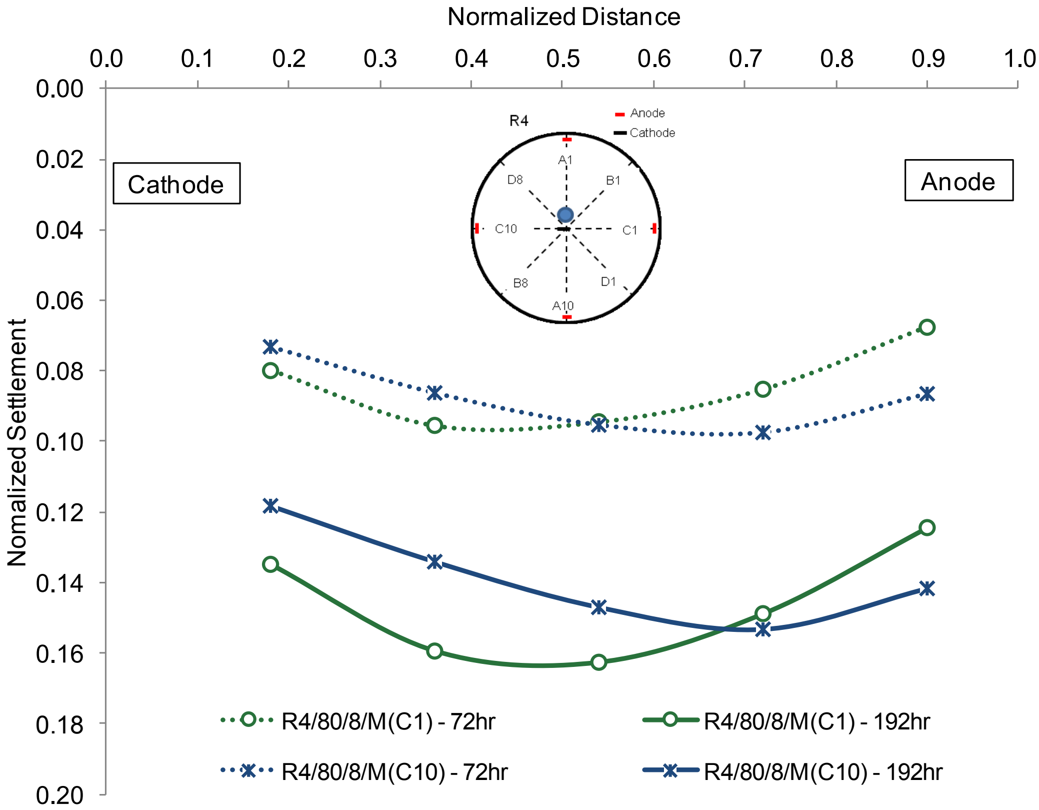
A 16: Variation in normalized settlement with time along Grid A in EO consolidation of peat in test with R4 electrode configuration at 80V/m



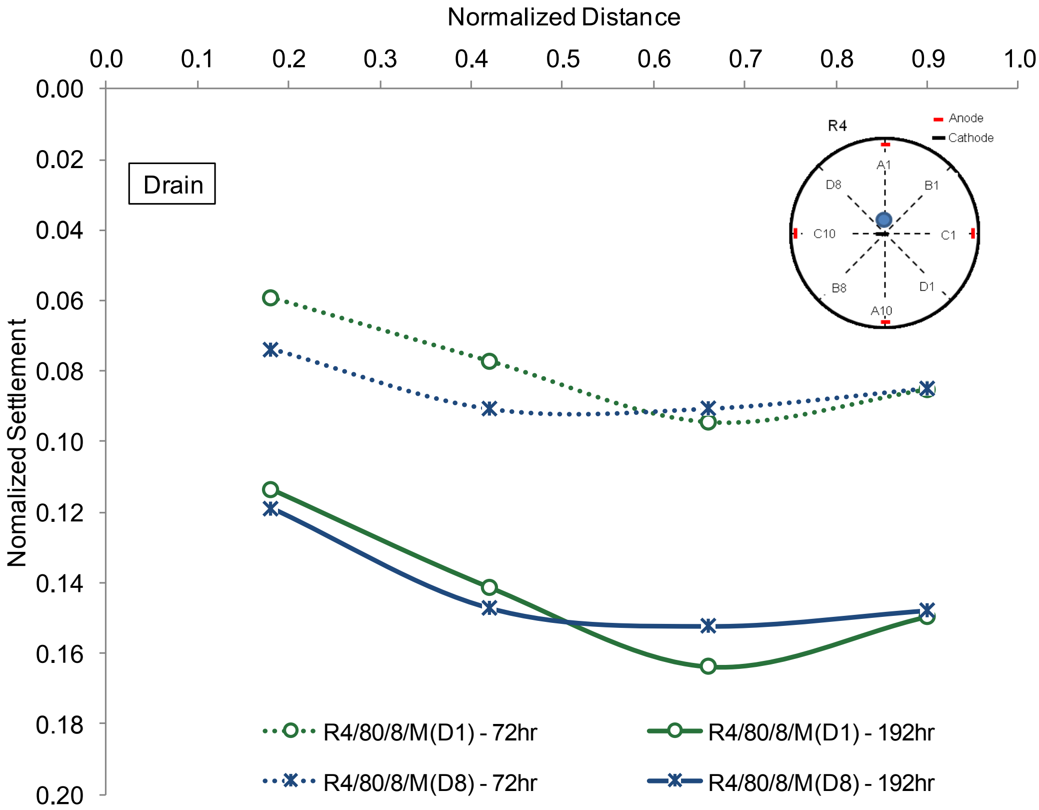
A 17: Variation in normalized settlement with time along Grid B in EO consolidation of peat in test with R4 electrode configuration at 80V/m



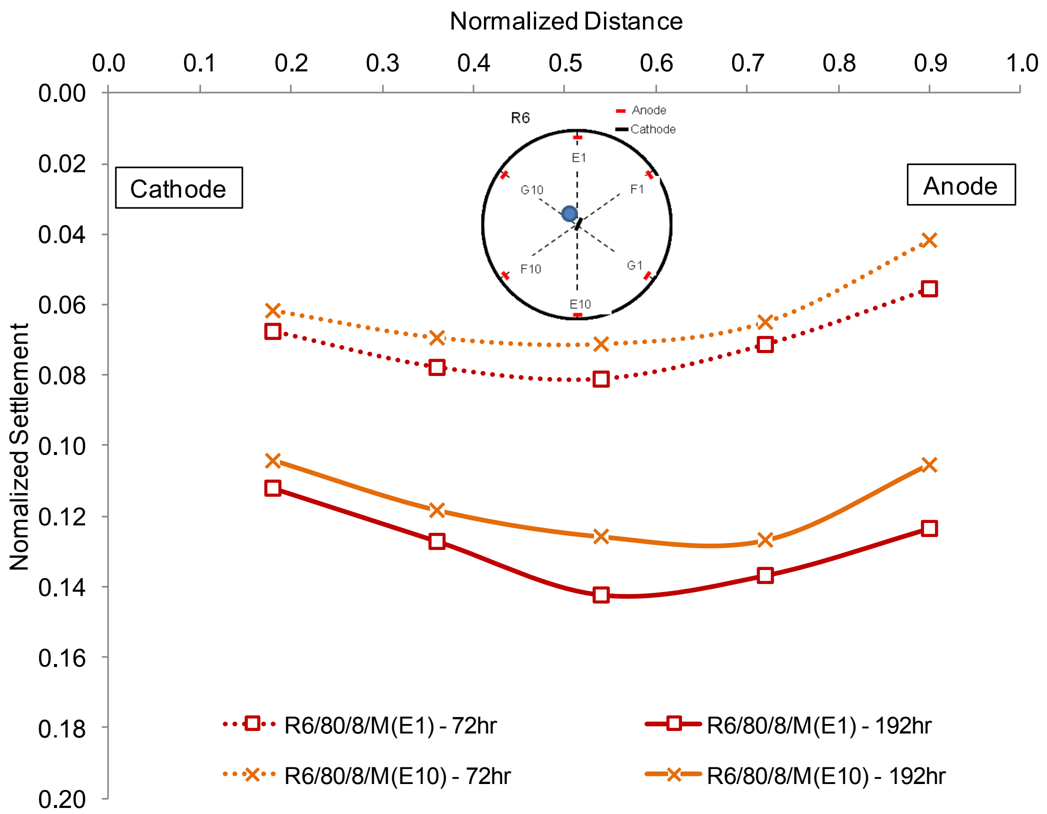
A 18: Variation in normalized settlement with time along Grid C in EO consolidation of peat in test with R4 electrode configuration at 80V/m



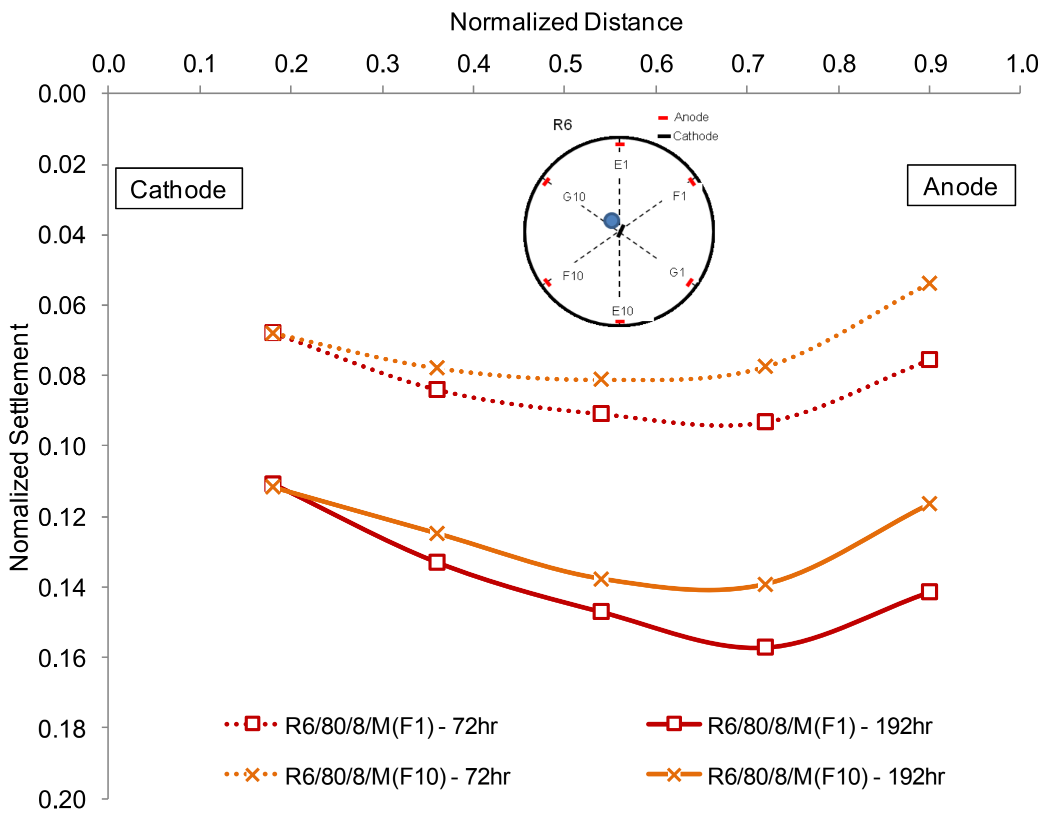
A 19: Variation in normalized settlement with time along Grid D in EO consolidation of peat in test with R4 electrode configuration at 80V/m



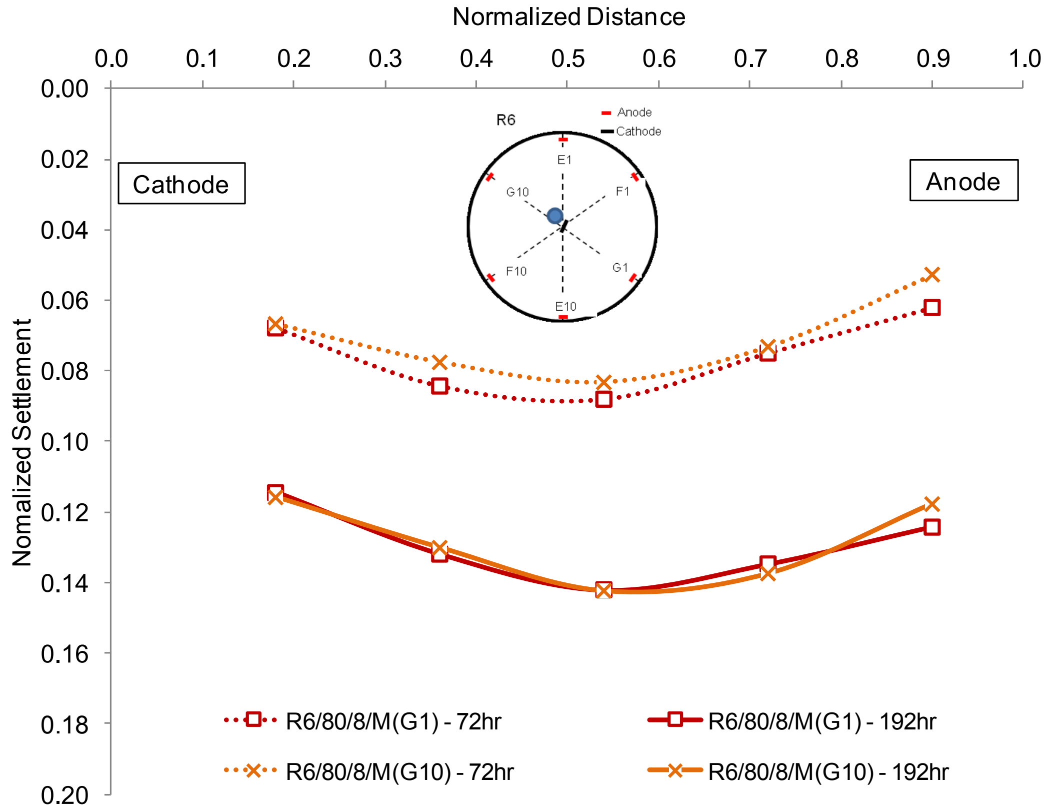
A 20: Variation in normalized settlement with time along Grid E in EO consolidation of peat in test with R6 electrode configuration at 80V/m



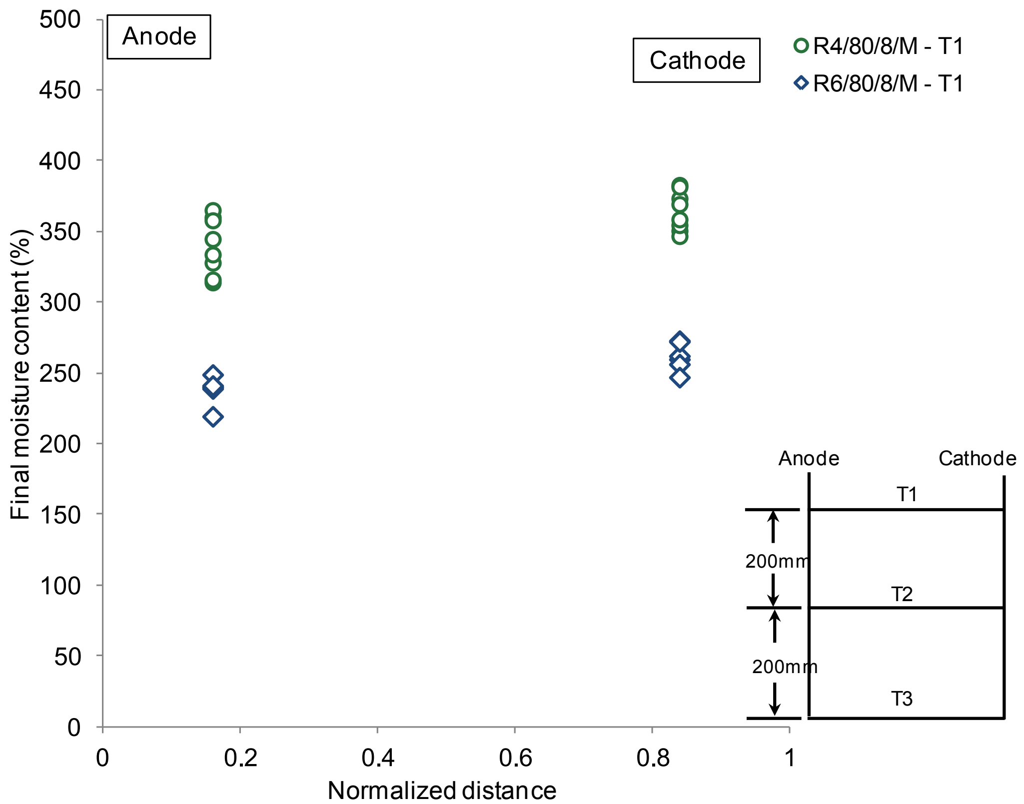
A 21: Variation in normalized settlement with time along Grid F in EO consolidation of peat in test with R6 electrode configuration at 80V/m



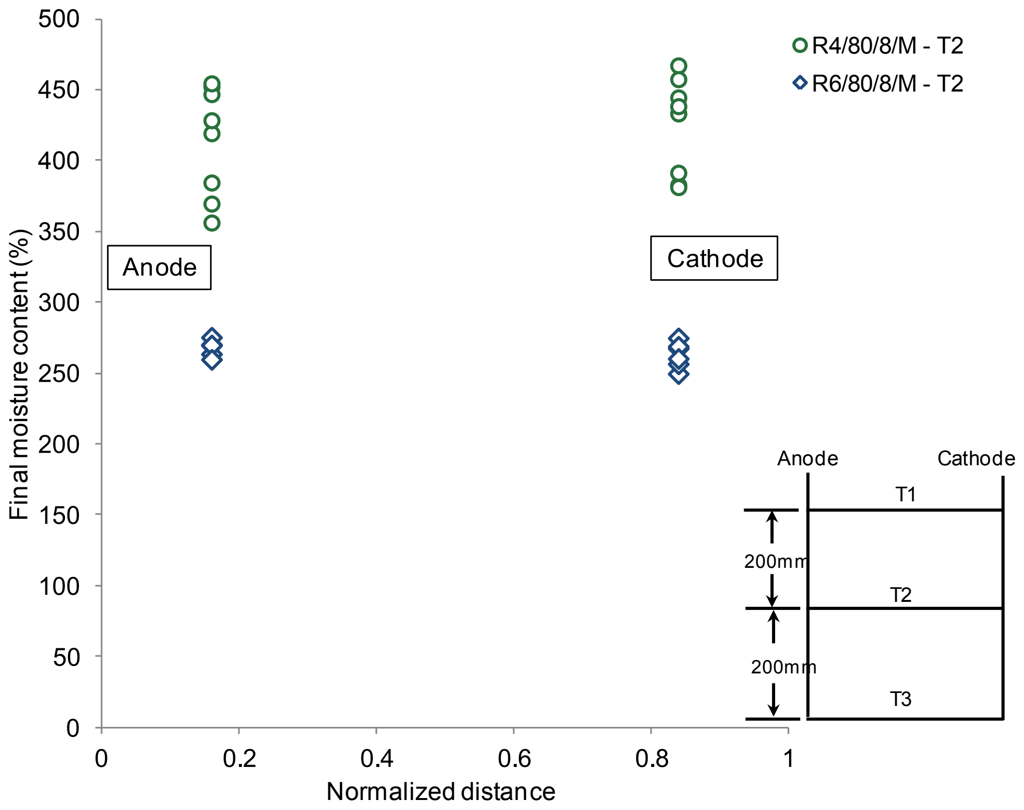
A 22: Variation in normalized settlement with time along Grid G in EO consolidation of peat in test with R6 electrode configuration at 80V/m



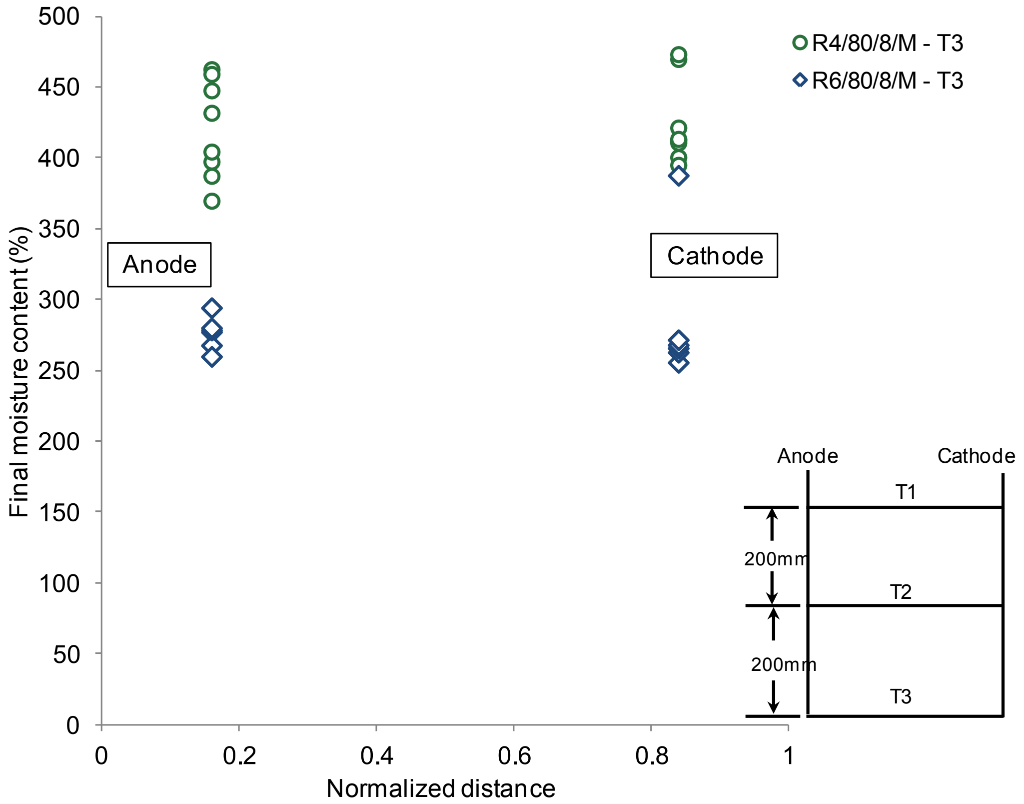
A 23: Final moisture contents at soil surface, T1, after EO consolidation with R4 and R6 electrode configuration at 80V/m



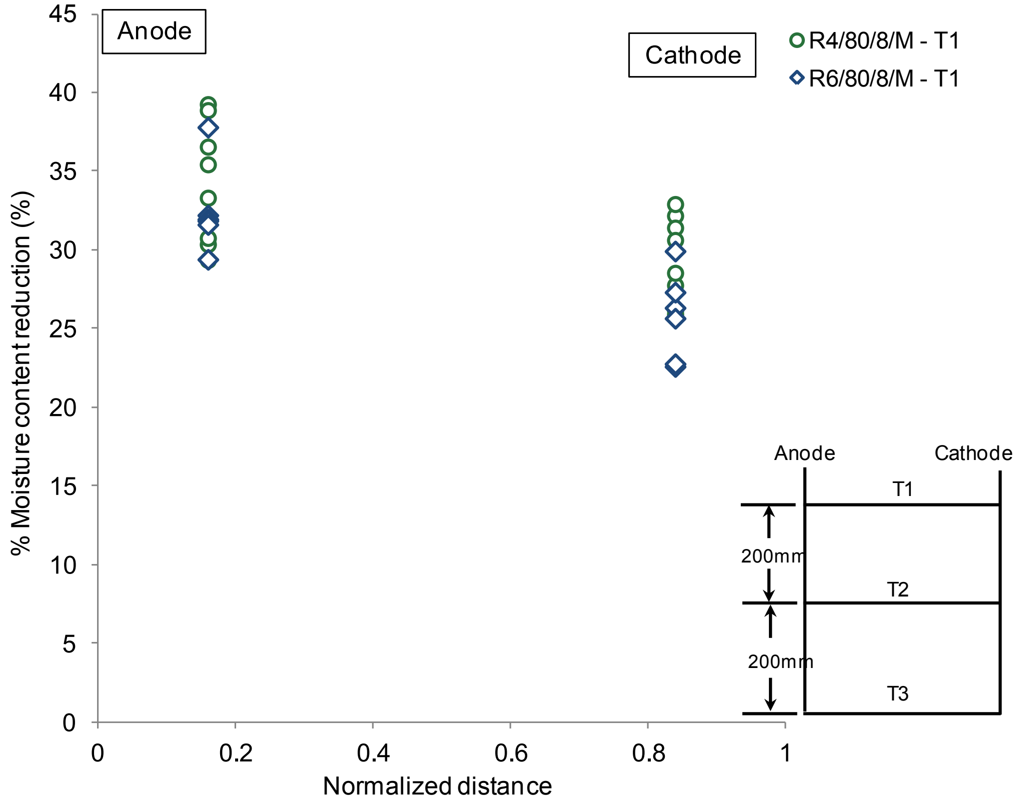
A 24: Final moisture contents at mid-depth, T2, after EO consolidation with R4 and R6 electrode configuration at 80V/m



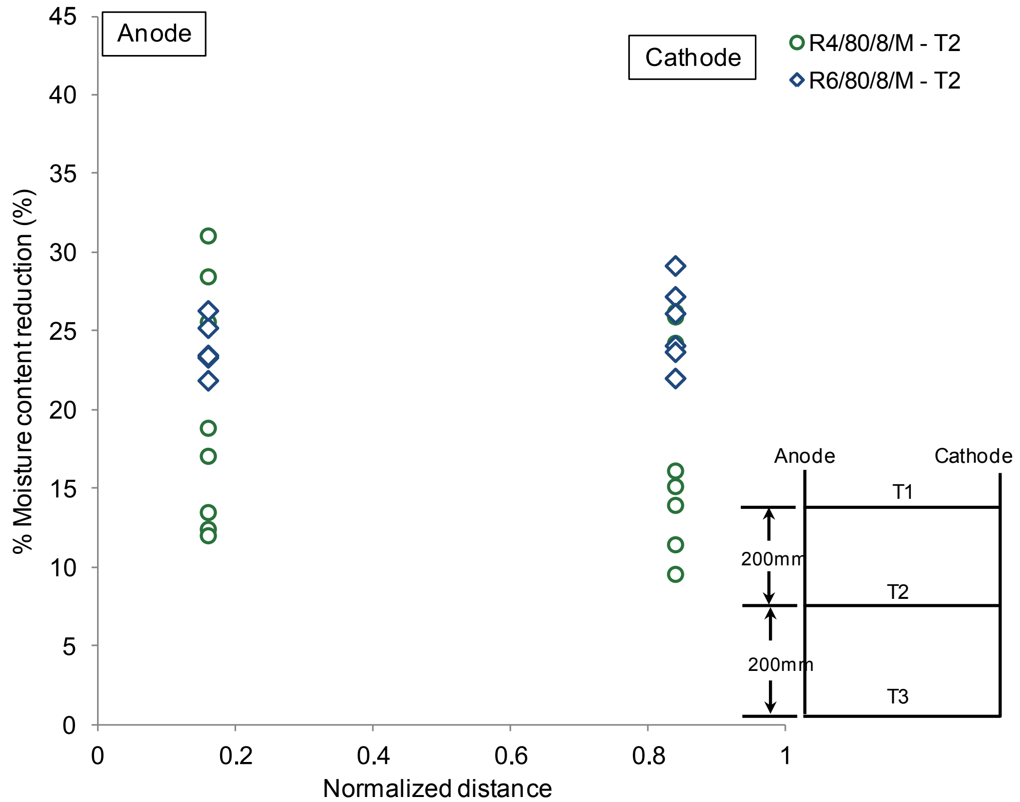
A 25: Final moisture contents at bottom of peat, T3, after EO consolidation with R4 and R6 electrode configuration at 80V/m



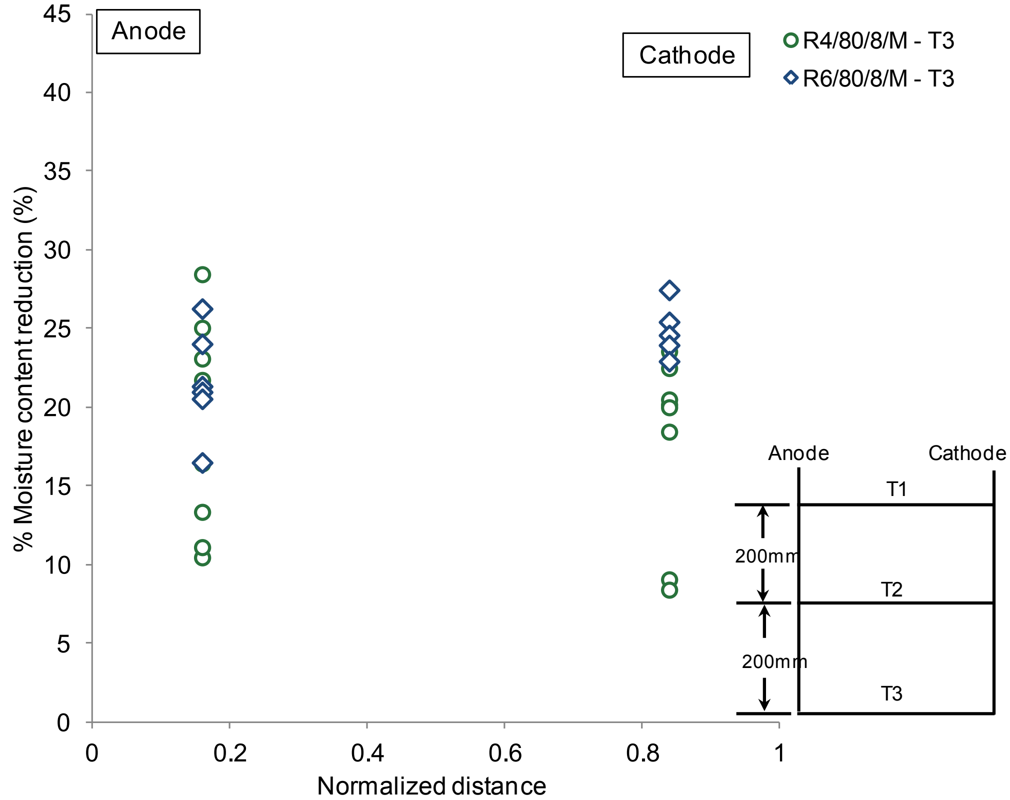
A 26: Moisture content reduction at soil surface, T1, after EO consolidation with R4 and R6 electrode configuration at 80V/m



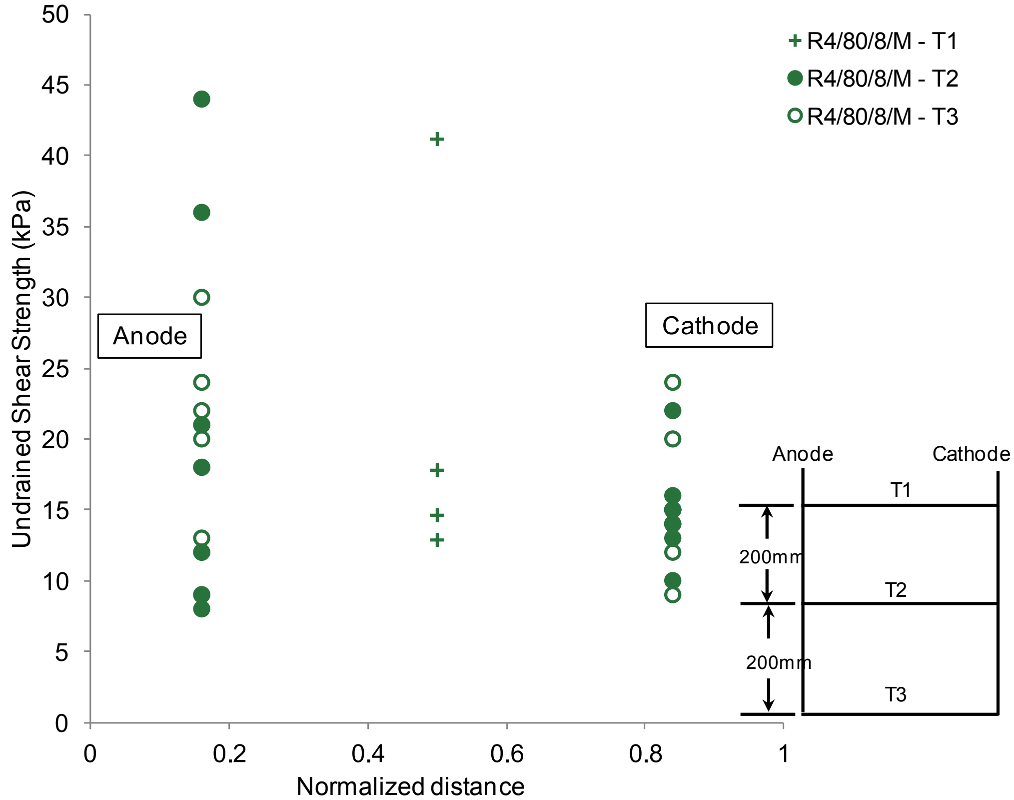
A 27: Moisture content reduction at mid-depth, T2, after EO consolidation with R4 and R6 electrode configuration at 80V/m



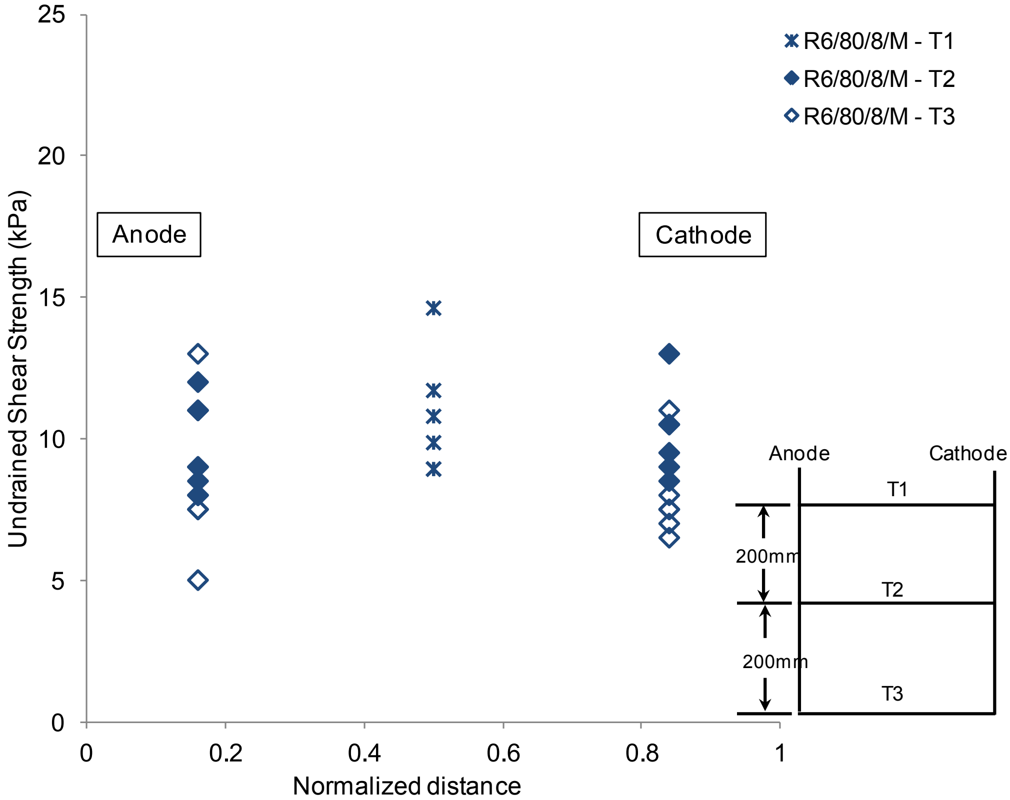
A 28: Moisture content reduction at bottom of peat, T3, after EO consolidation with R4 and R6 electrode configuration at 80V/m



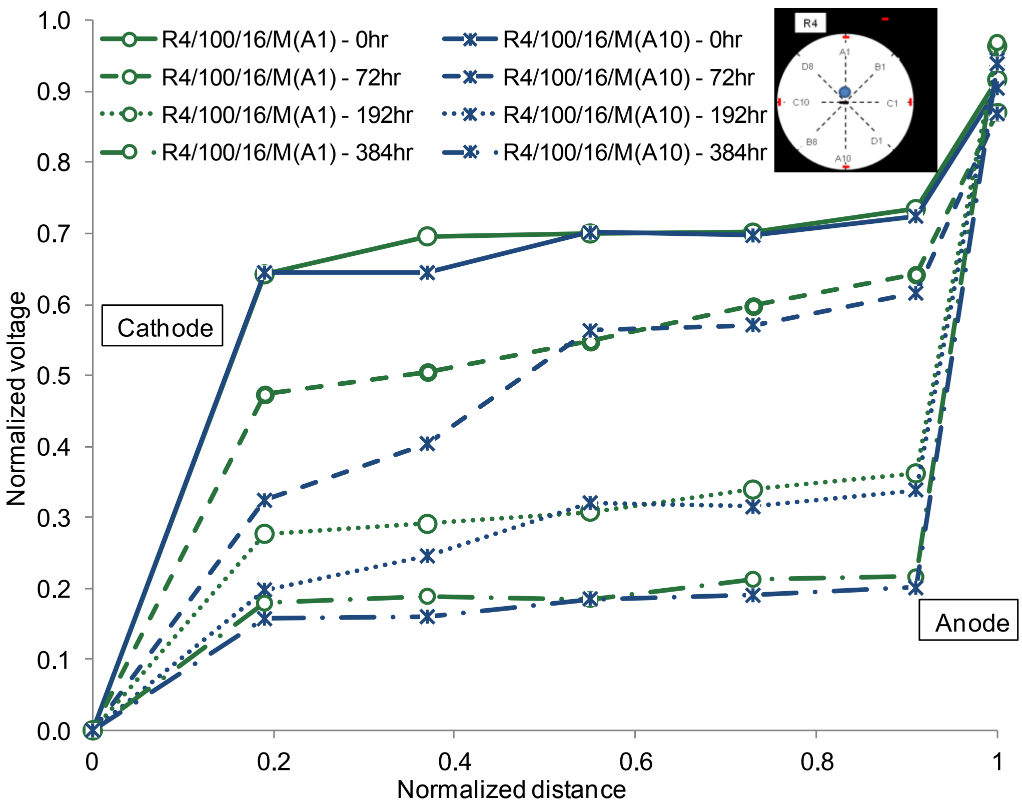
A 29: Final undrained shear strength at surface (T1), mid-depth (T2) and bottom (T3) of peat in test with R4 electrode configuration at 80V/m



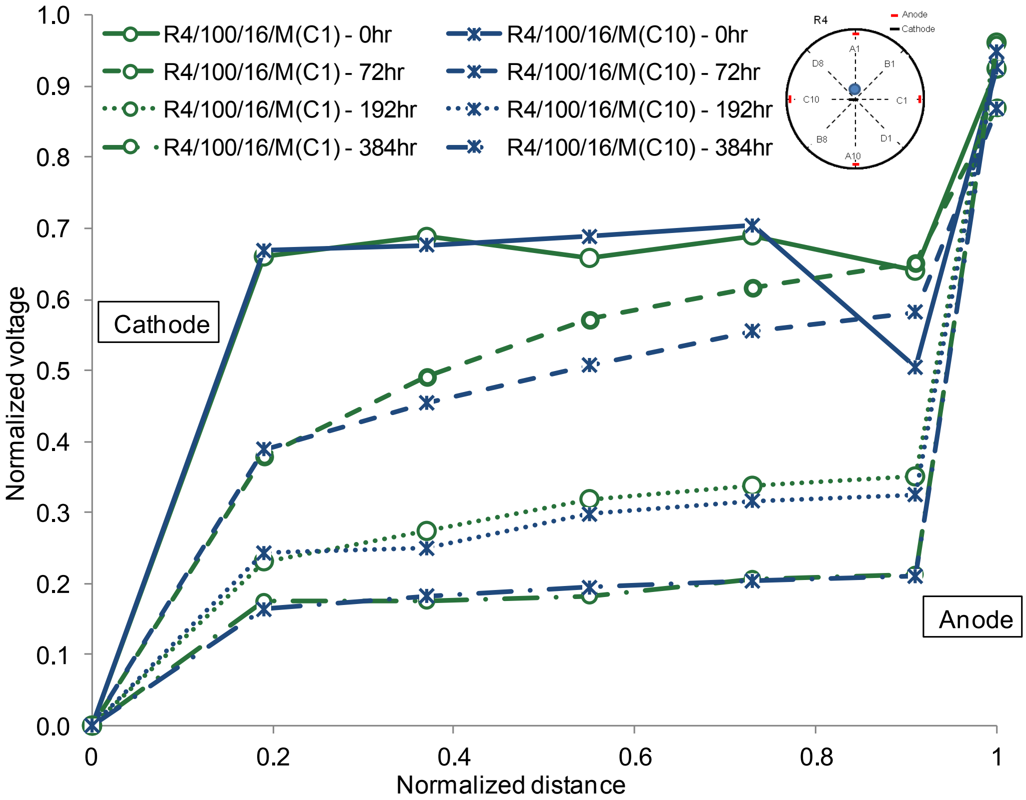
A 30: Final undrained shear strength at surface (T1), mid-depth (T2) and bottom (T3) of peat in test with R6 electrode configuration at 80V/m



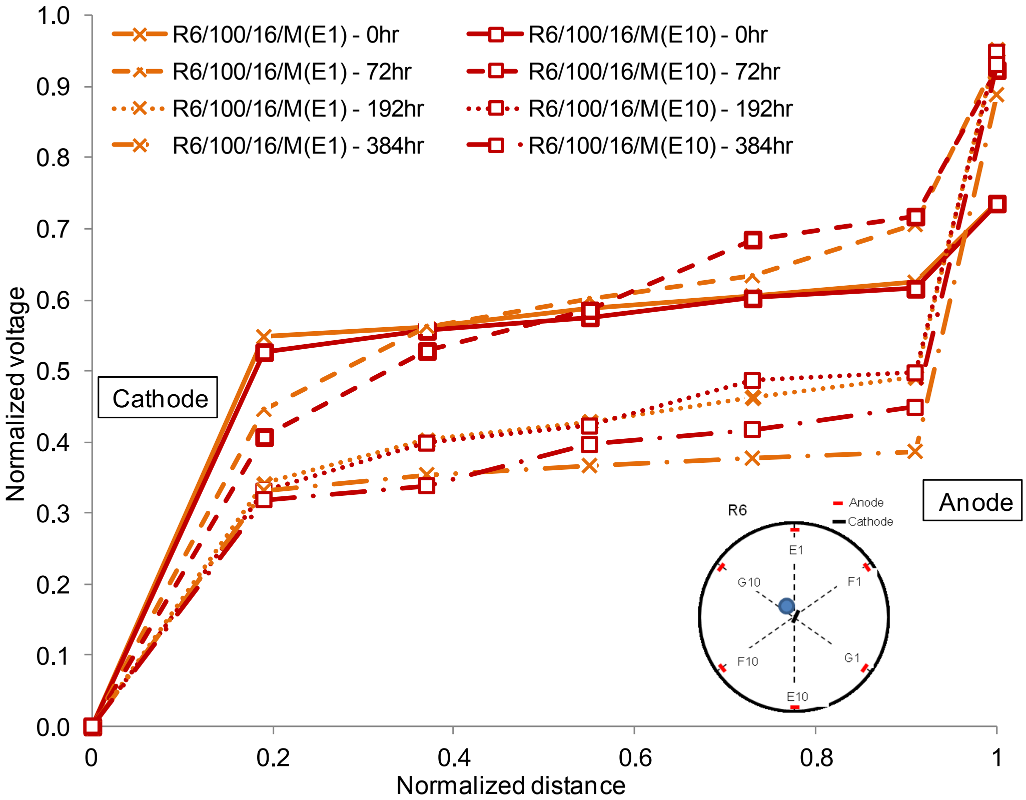
A 31: Variation in measured voltage with time along Grid A in EO consolidation of peat in test with R4 electrode configuration at 100V/m



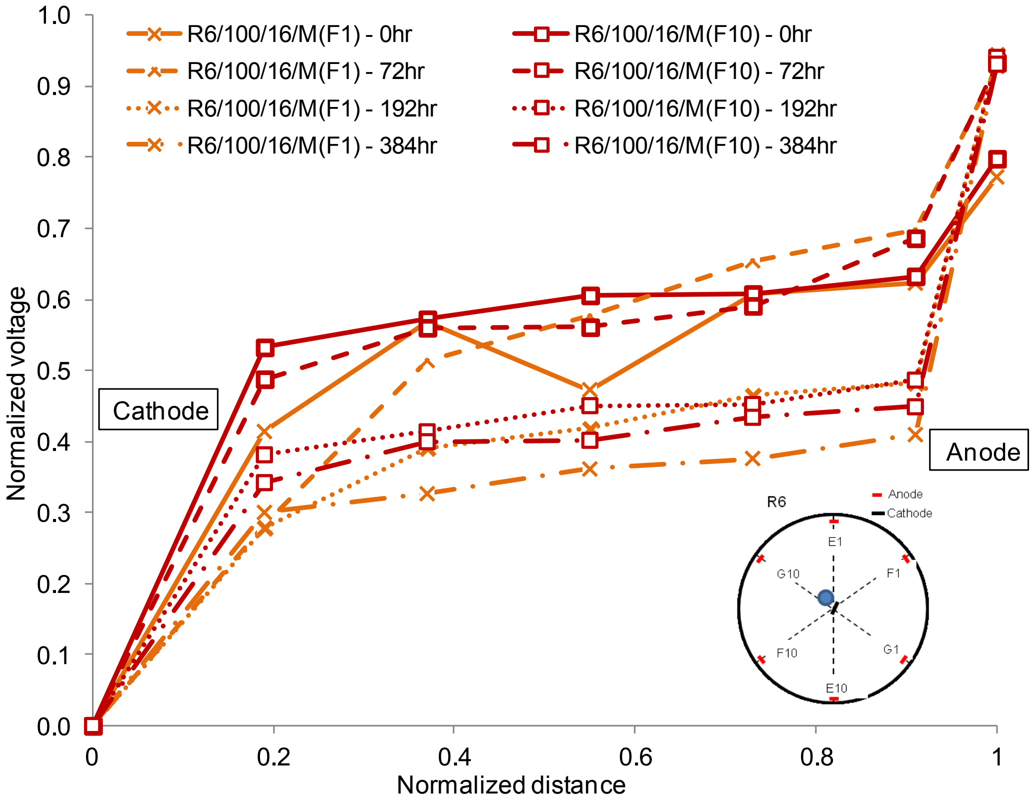
A 32: Variation in measured voltage with time along Grid C in EO consolidation of peat in test with R4 electrode configuration at 100V/m



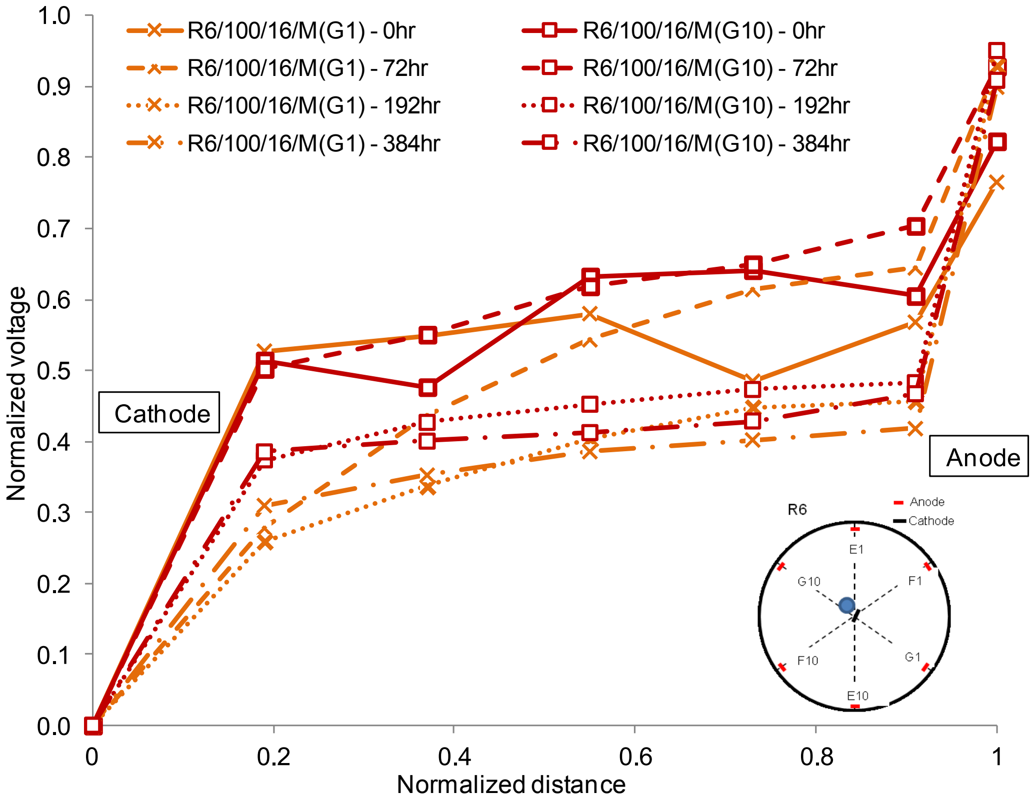
A 33: Variation in measured voltage with time along Grid E in EO consolidation of peat in test with R6 electrode configuration at 100V/m



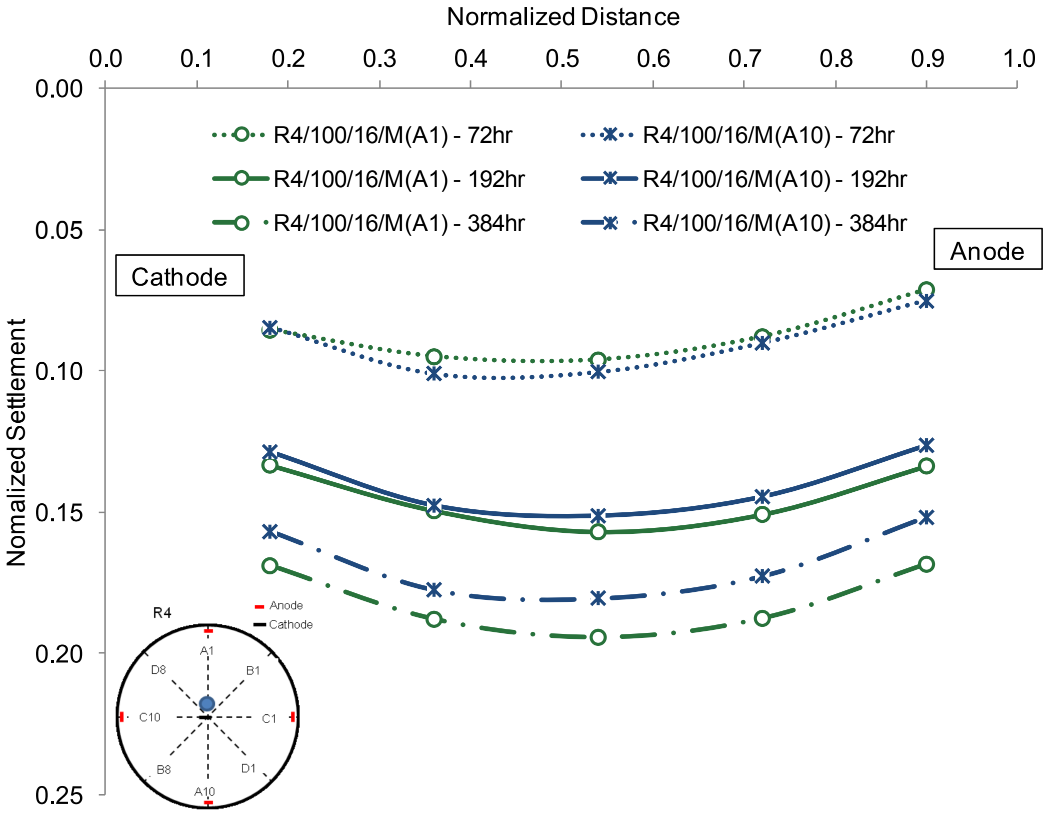
A 34: Variation in measured voltage with time along Grid F in EO consolidation of peat in test with R6 electrode configuration at 100V/m



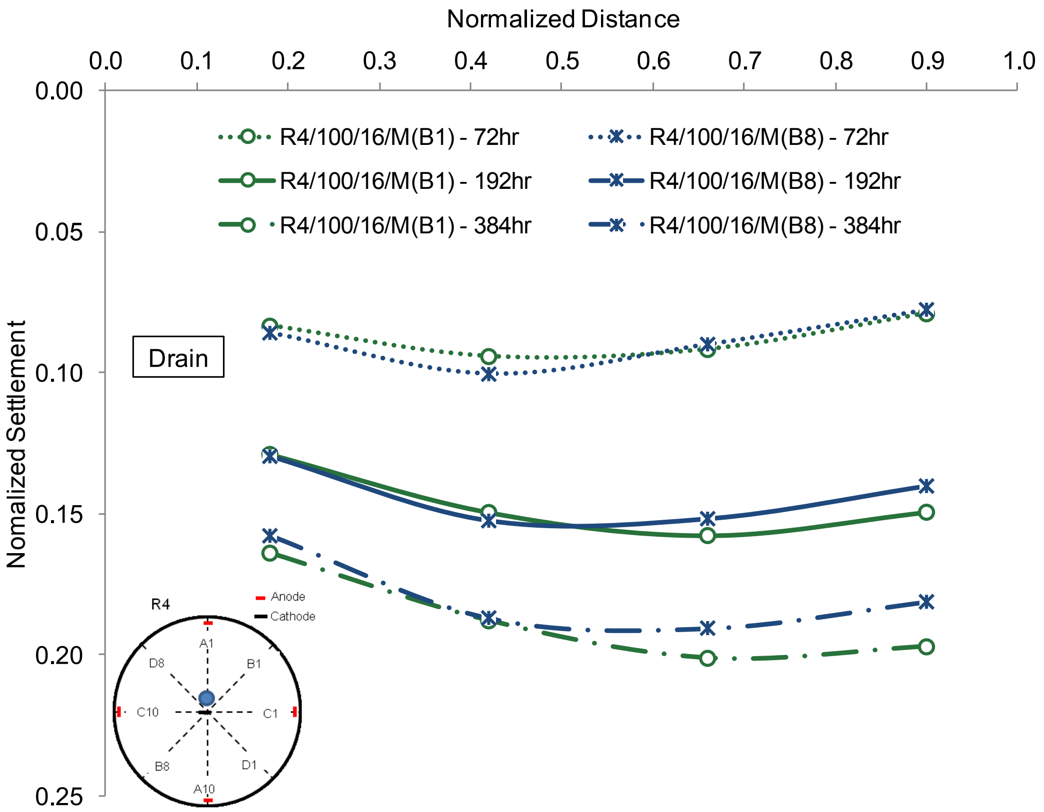
A 35: Variation in measured voltage with time along Grid G in EO consolidation of peat in test with R6 electrode configuration at 100V/m



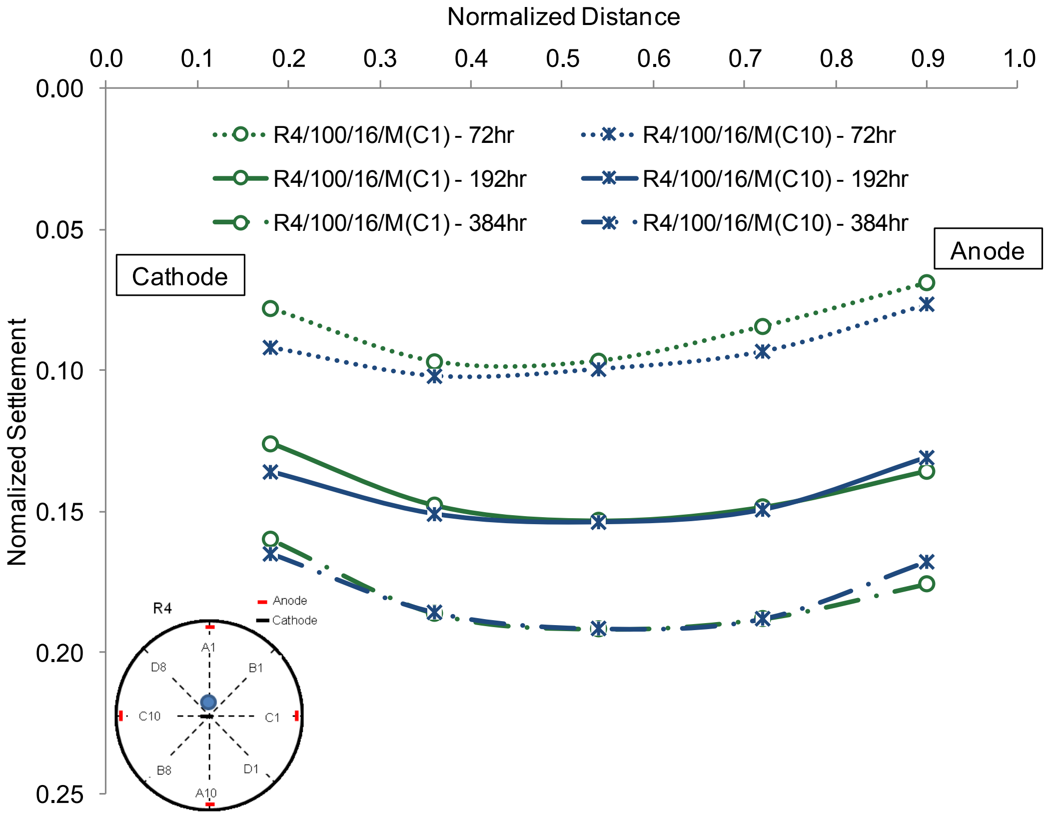
A 36: Variation in normalized settlement with time along Grid A in EO consolidation of peat in test with R4 electrode configuration at 100V/m



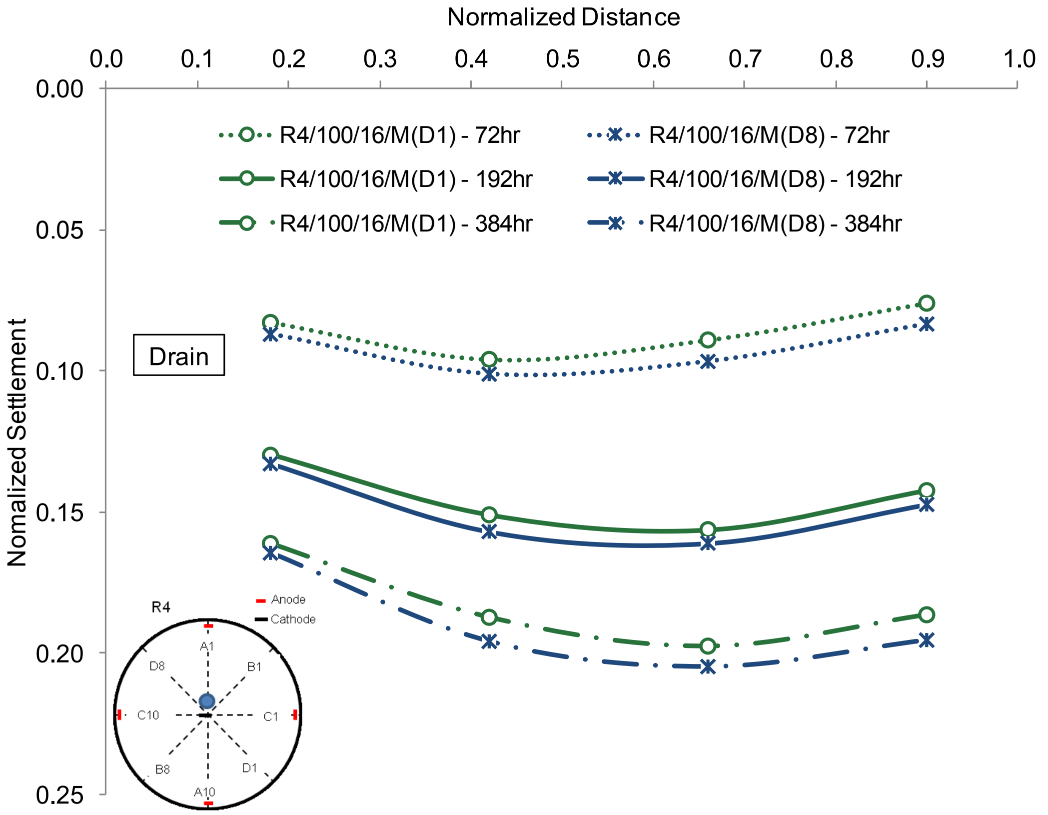
A 37: Variation in normalized settlement with time along Grid B in EO consolidation of peat in test with R4 electrode configuration at 100V/m



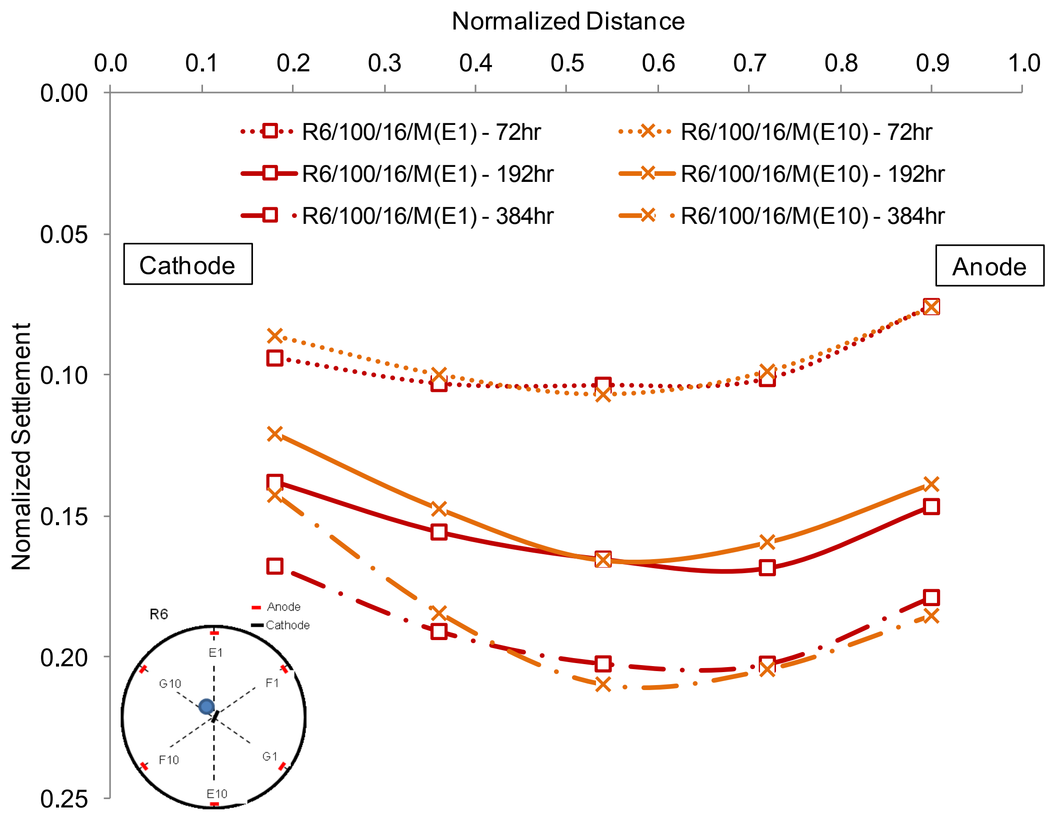
A 38: Variation in normalized settlement with time along Grid C in EO consolidation of peat in test with R4 electrode configuration at 100V/m



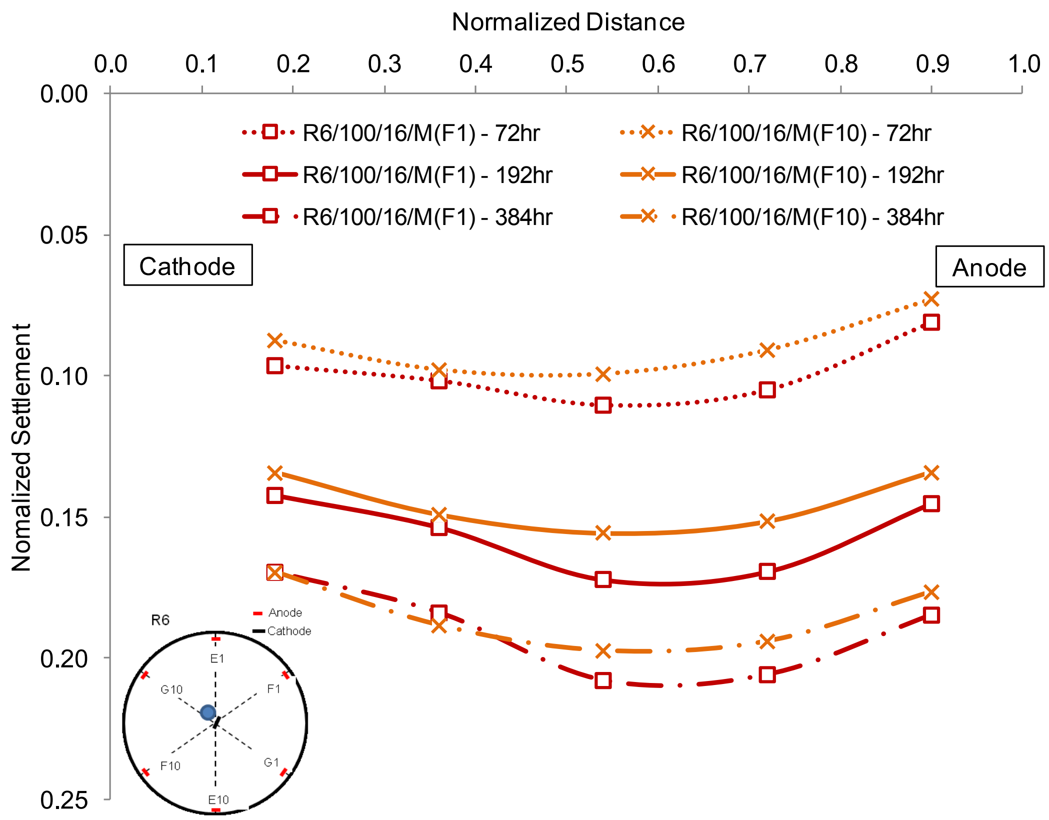
A 39: Variation in normalized settlement with time along Grid D in EO consolidation of peat in test with R4 electrode configuration at 100V/m



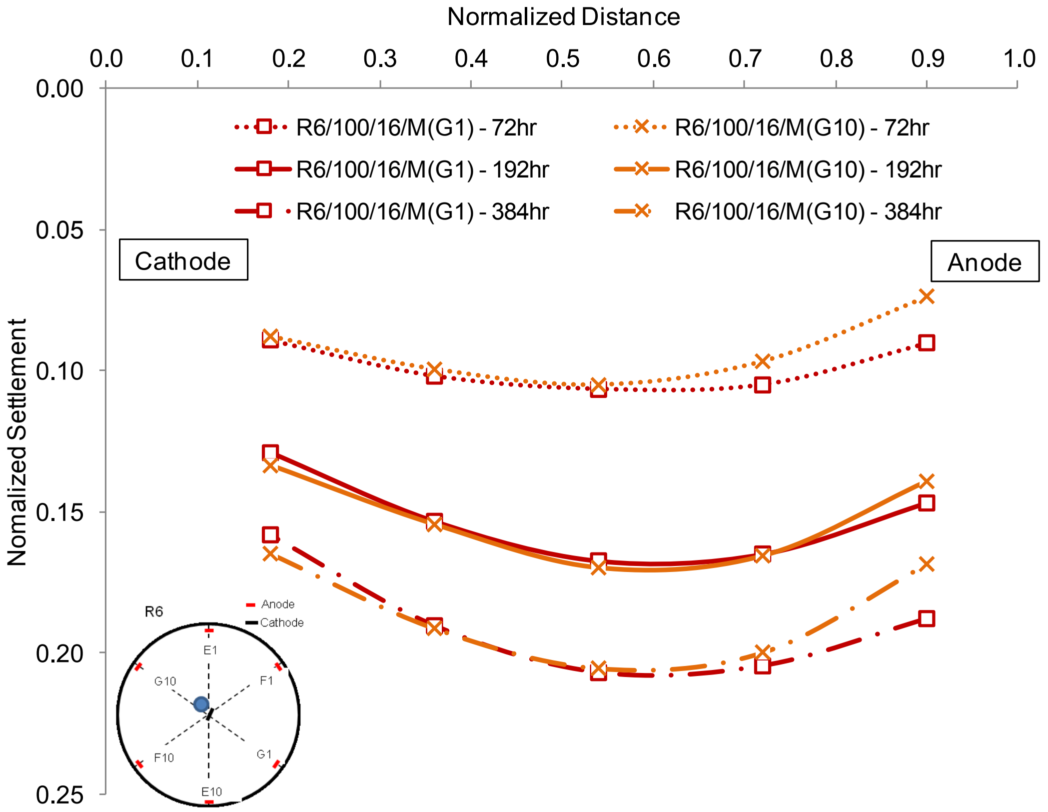
A 40: Variation in normalized settlement with time along Grid E in EO consolidation of peat in test with R6 electrode configuration at 100V/m



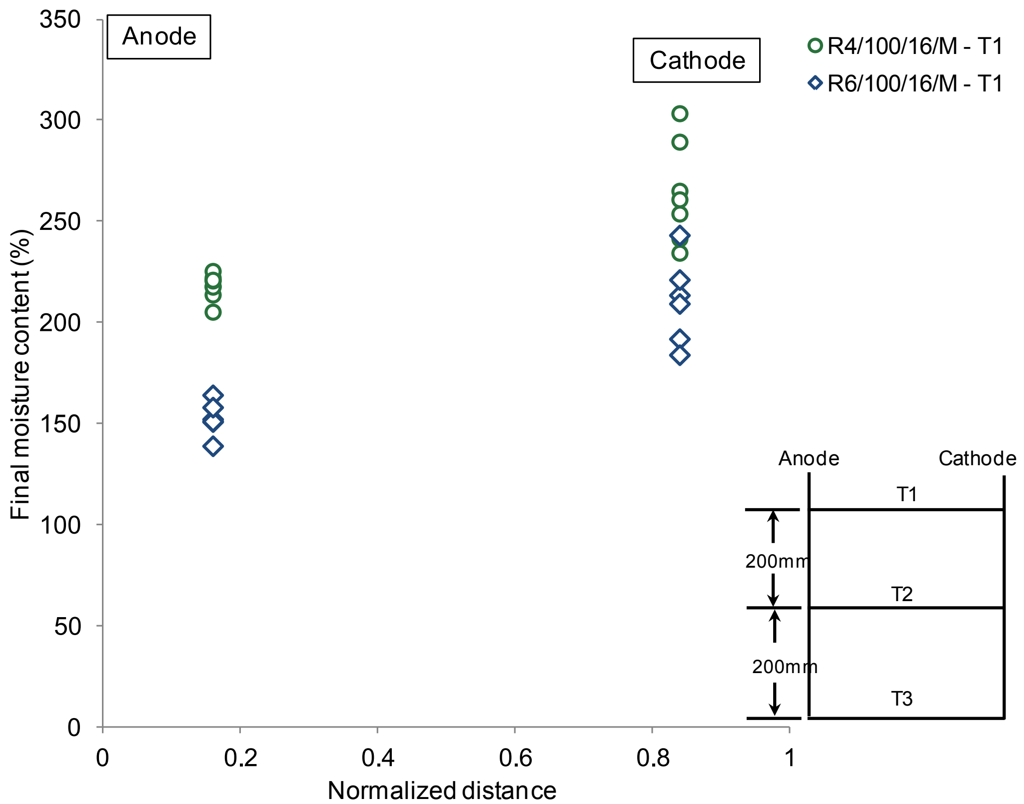
A 41: Variation in normalized settlement with time along Grid F in EO consolidation of peat in test with R6 electrode configuration at 100V/m



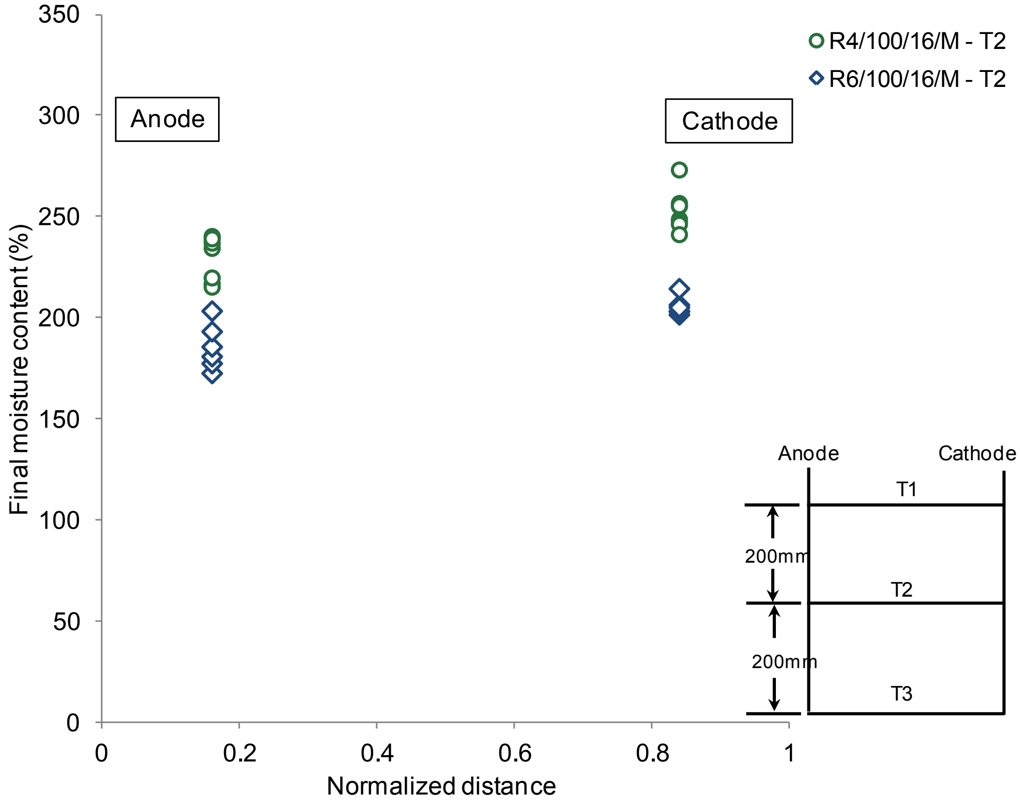
A 42: Variation in normalized settlement with time along Grid G in EO consolidation of peat in test with R6 electrode configuration at 100V/m



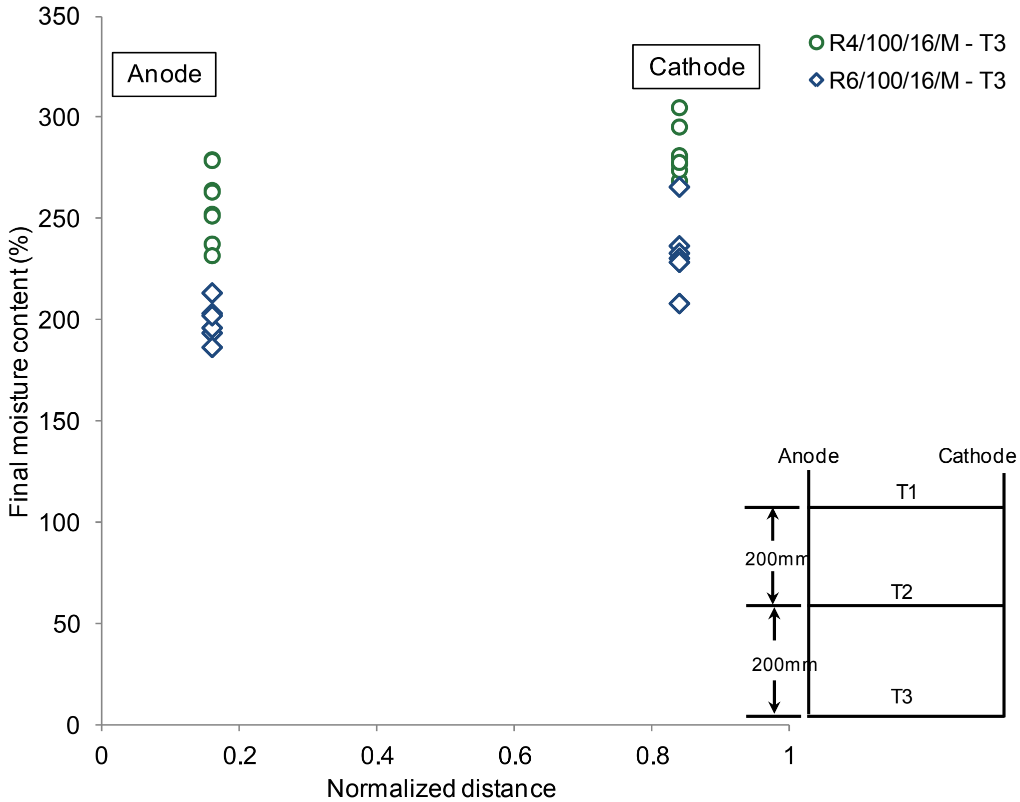
A 43: Final moisture contents at soil surface, T1, after EO consolidation with R4 and R6 electrode configuration at 100V/m



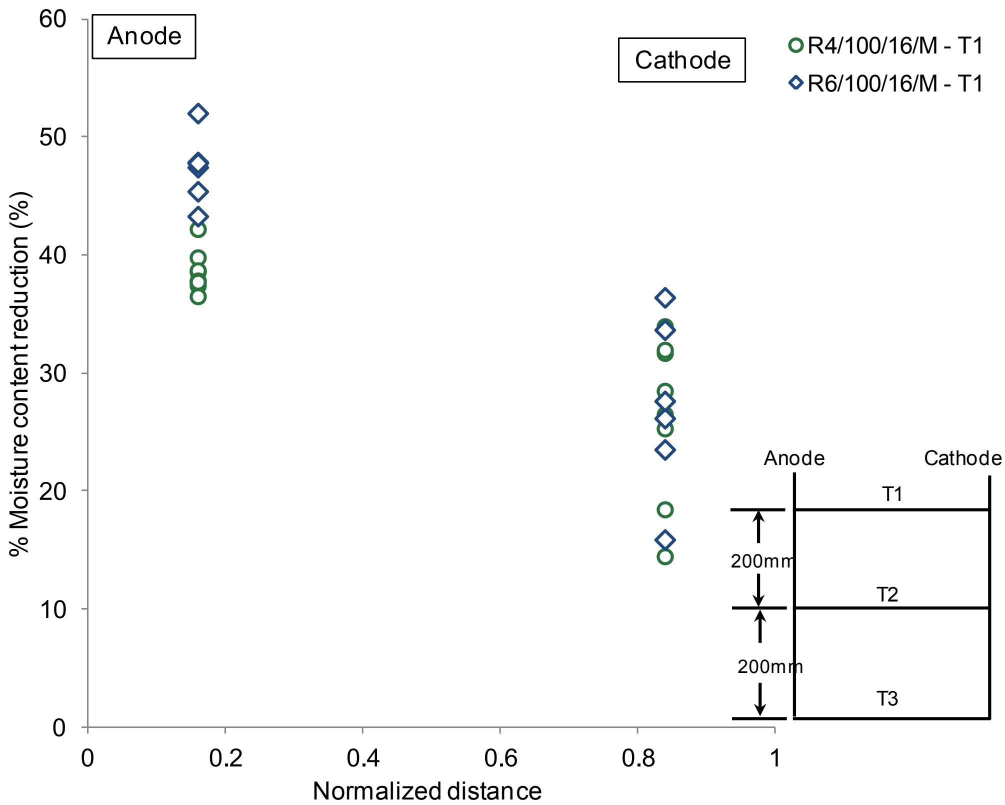
A 44: Final moisture contents at mid-depth, T2, after EO consolidation with R4 and R6 electrode configuration at 100V/m



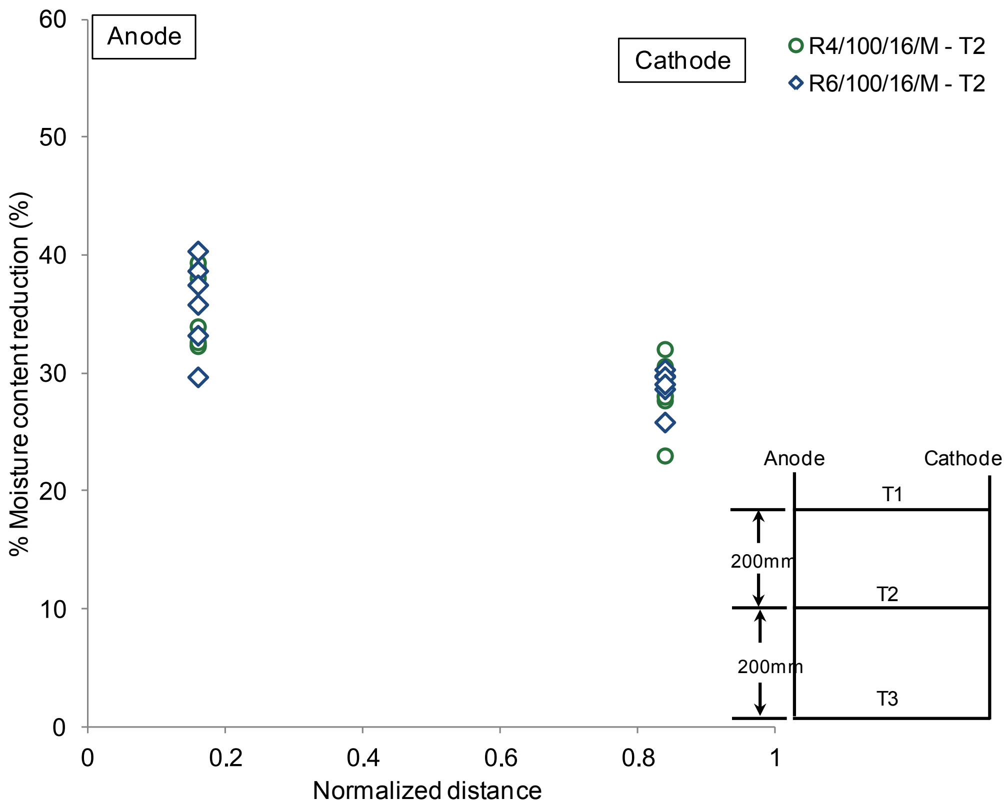
A 45: Final moisture contents at bottom of peat, T3, after EO consolidation with R4 and R6 electrode configuration at 100V/m



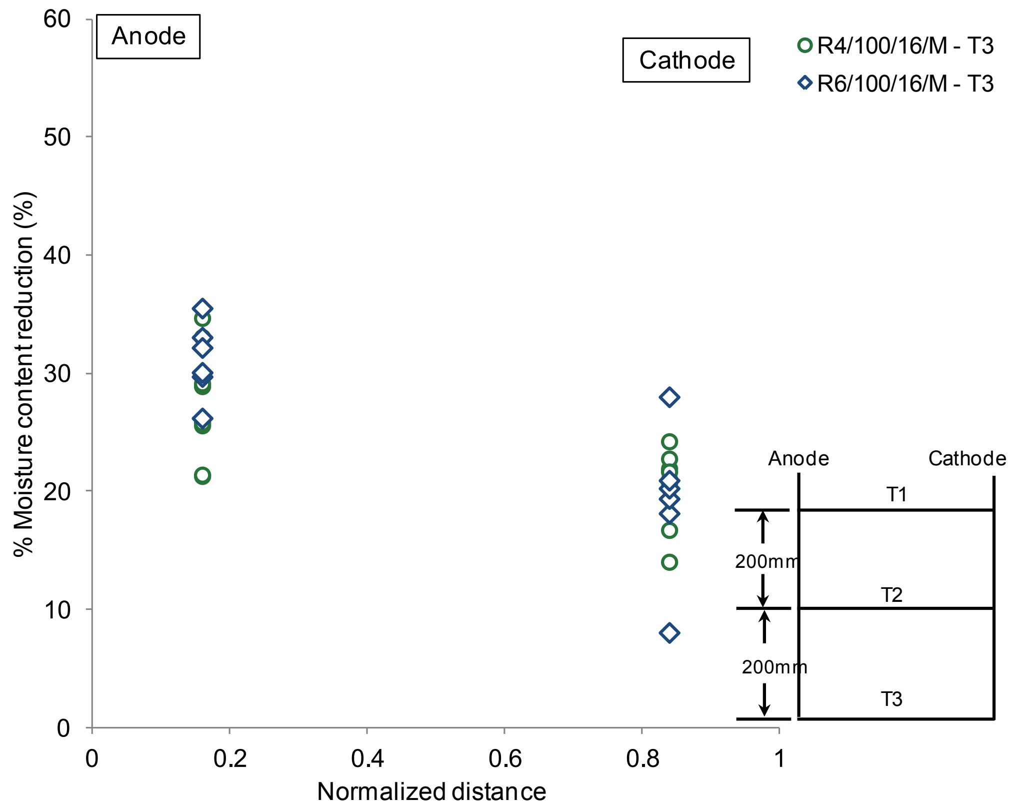
A 46: Moisture content reduction at soil surface, T1, after EO consolidation with R4 and R6 electrode configuration at 100V/m



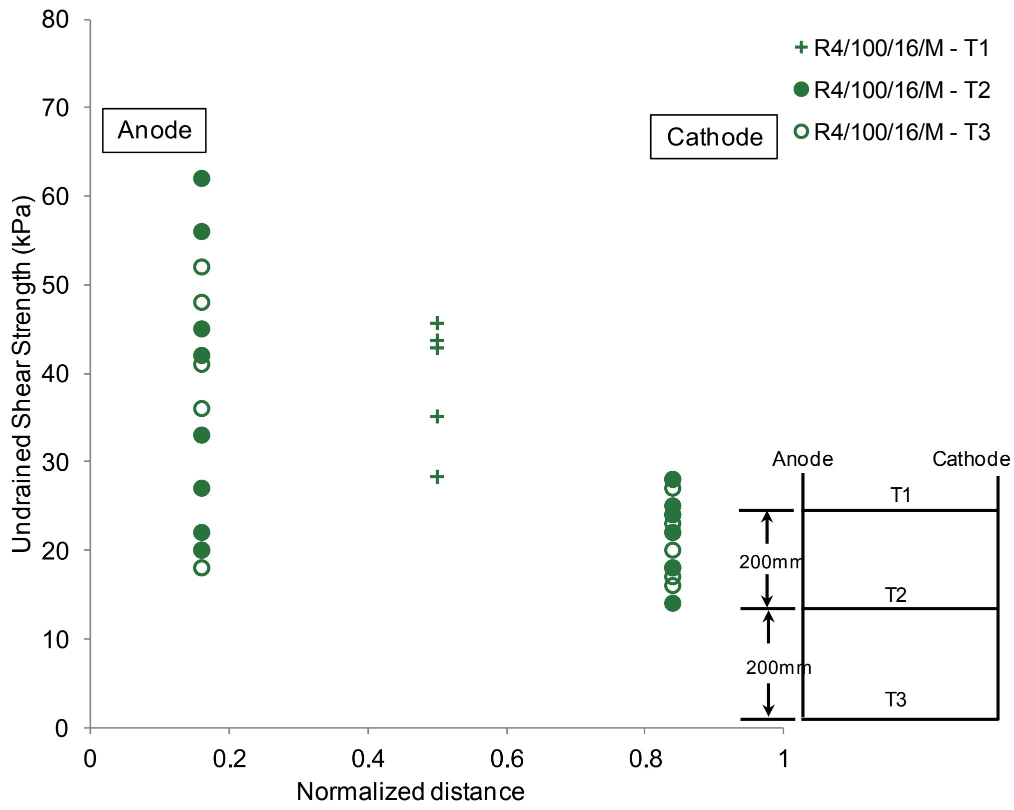
A 47: Moisture content reduction at mid-depth, T2, after EO consolidation with R4 and R6 electrode configuration at 100V/m



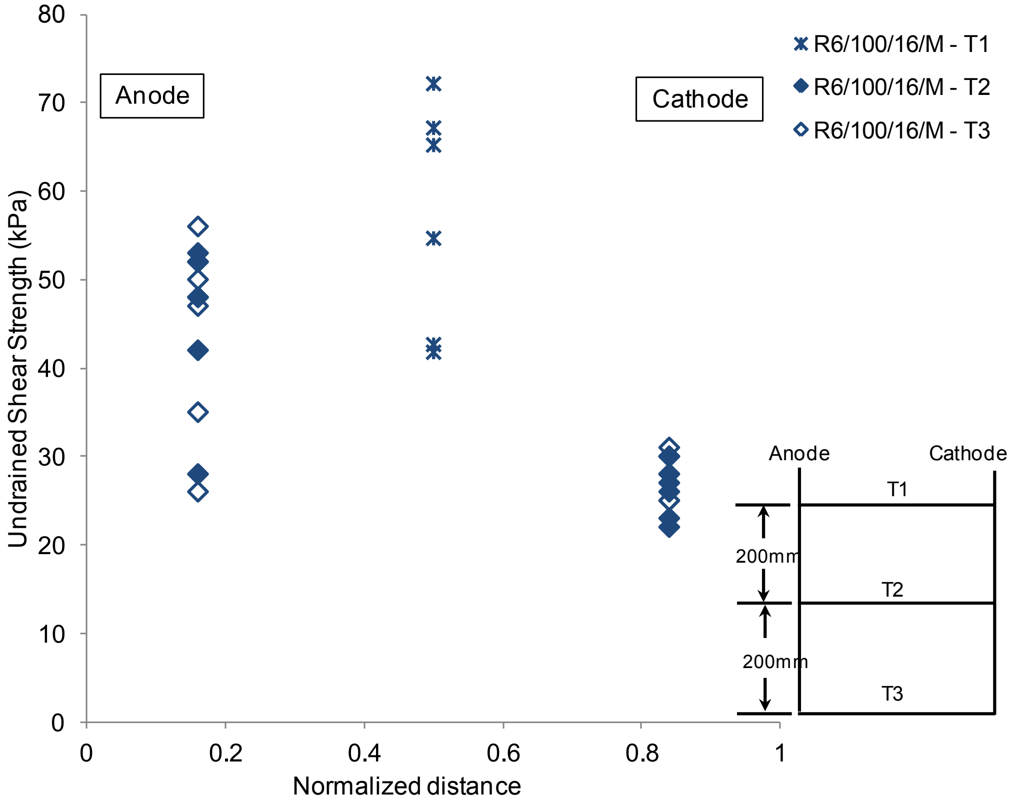
A 48: Moisture content reduction at bottom of peat, T3, after EO consolidation with R4 and R6 electrode configuration at 100V/m



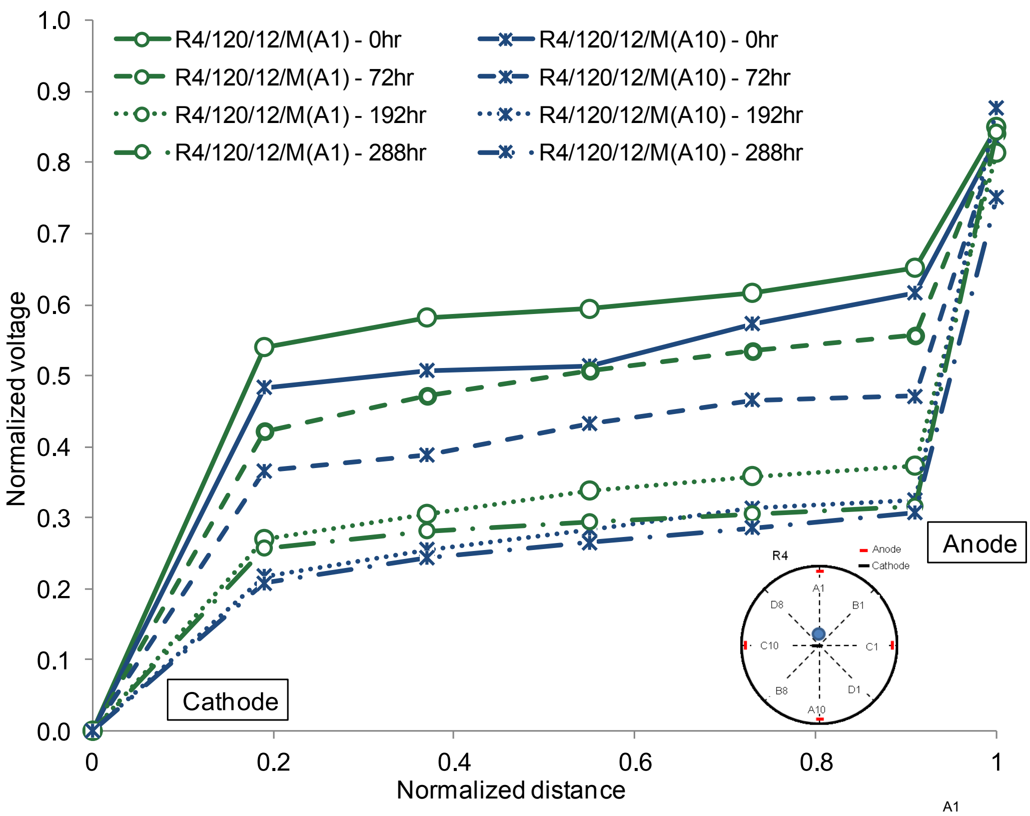
A 49: Final undrained shear strength at surface (T1), mid-depth (T2) and bottom (T3) of peat in test with R4 electrode configuration at 100V/m



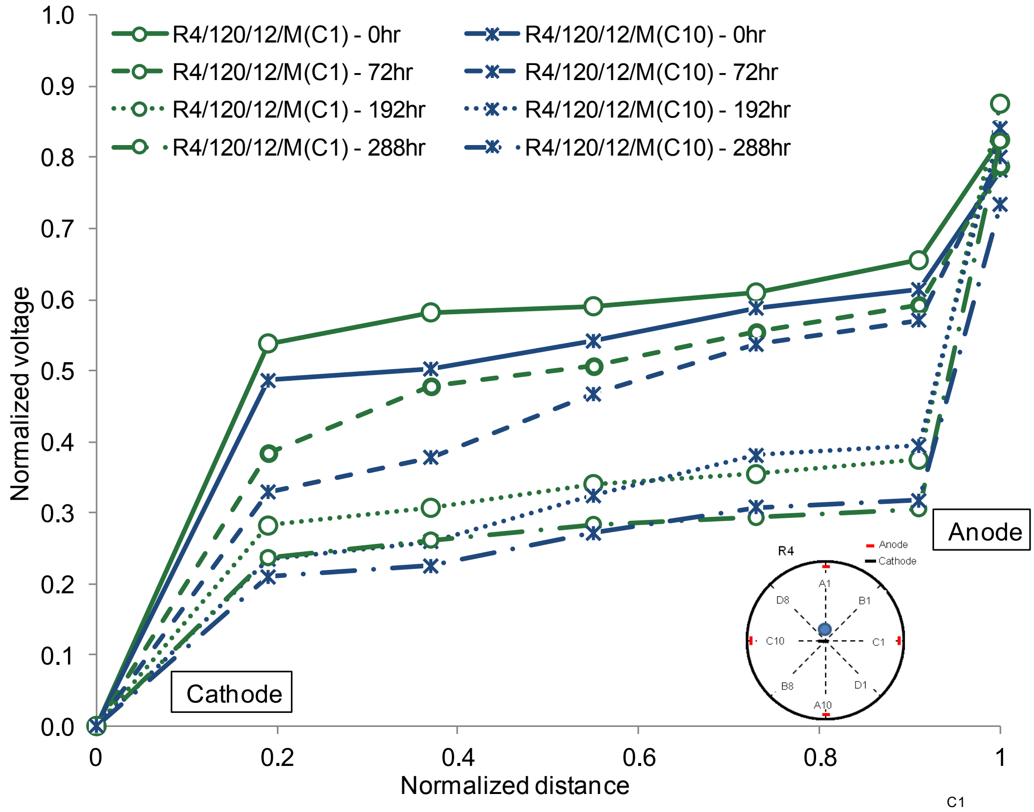
A 50: Final undrained shear strength at surface (T1), mid-depth (T2) and bottom (T3) of peat in test with R6 electrode configuration at 100V/m



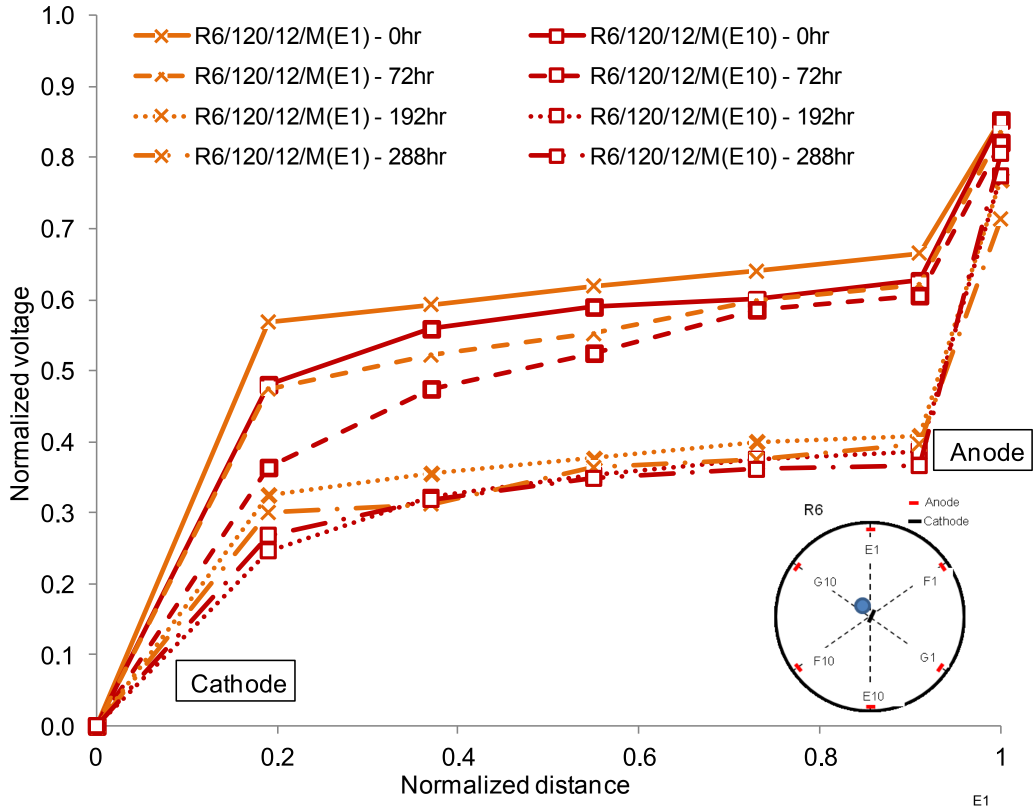
A 51: Variation in measured voltage with time along Grid A in EO consolidation of peat in test with R4 electrode configuration at 120V/m



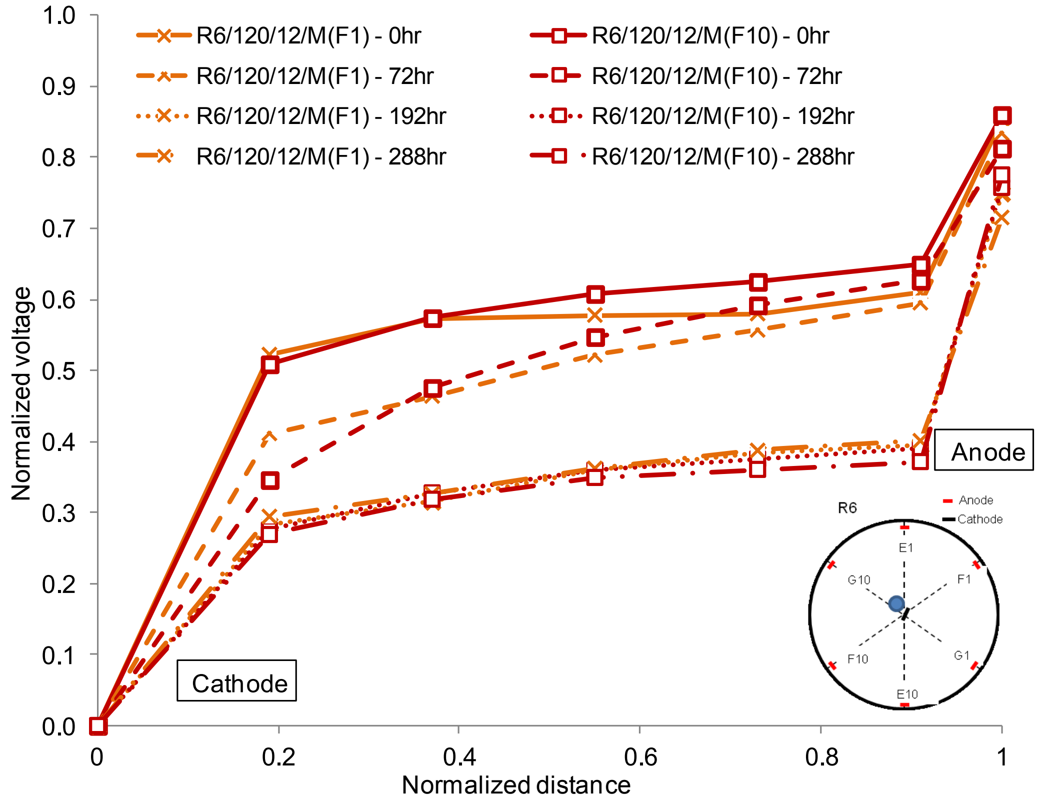
A 52: Variation in measured voltage with time along Grid C in EO consolidation of peat in test with R4 electrode configuration at 120V/m



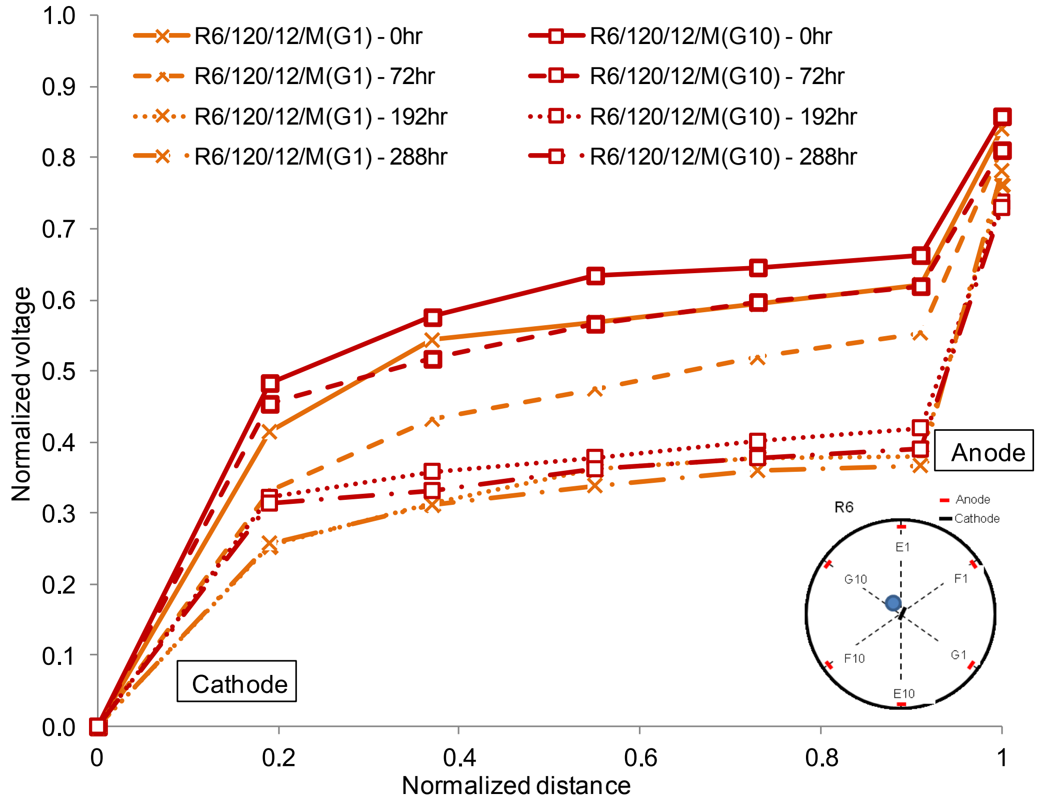
A 53: Variation in measured voltage with time along Grid E in EO consolidation of peat in test with R6 electrode configuration at 120V/m



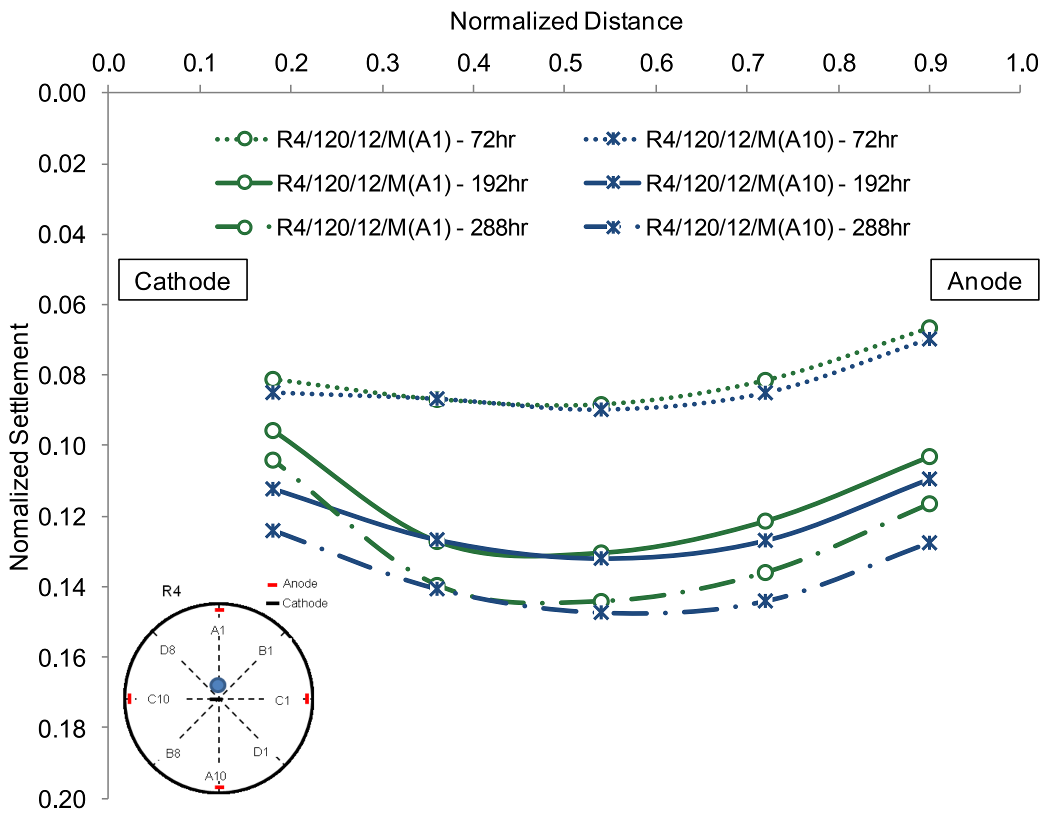
A 54: Variation in measured voltage with time along Grid F in EO consolidation of peat in test with R6 electrode configuration at 120V/m



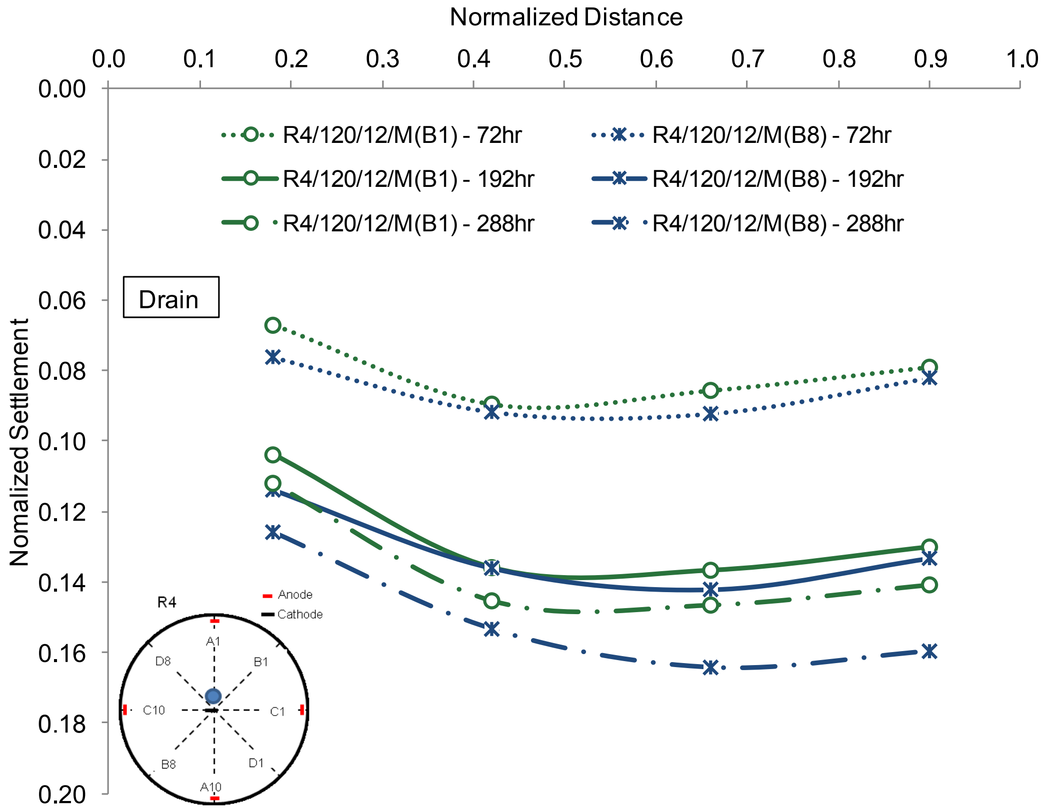
A 55: Variation in measured voltage with time along Grid G in EO consolidation of peat in test with R6 electrode configuration at 120V/m



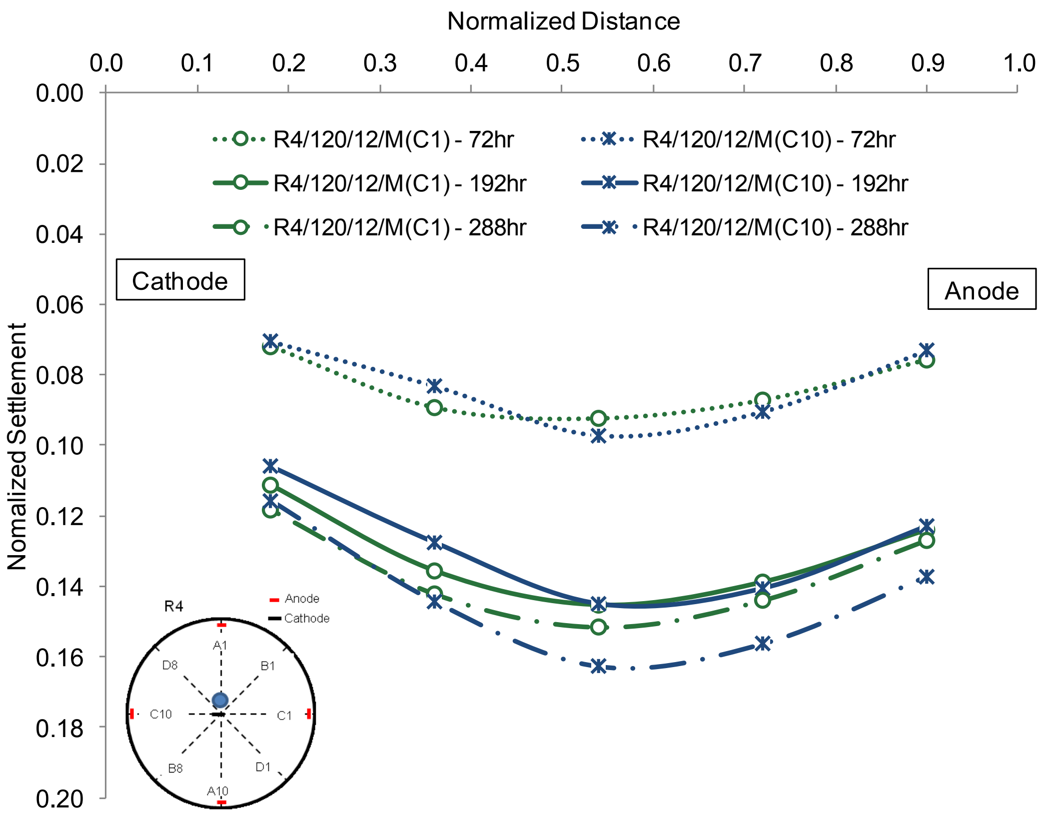
A 56: Variation in normalized settlement with time along Grid A in EO consolidation of peat in test with R4 electrode configuration at 120V/m



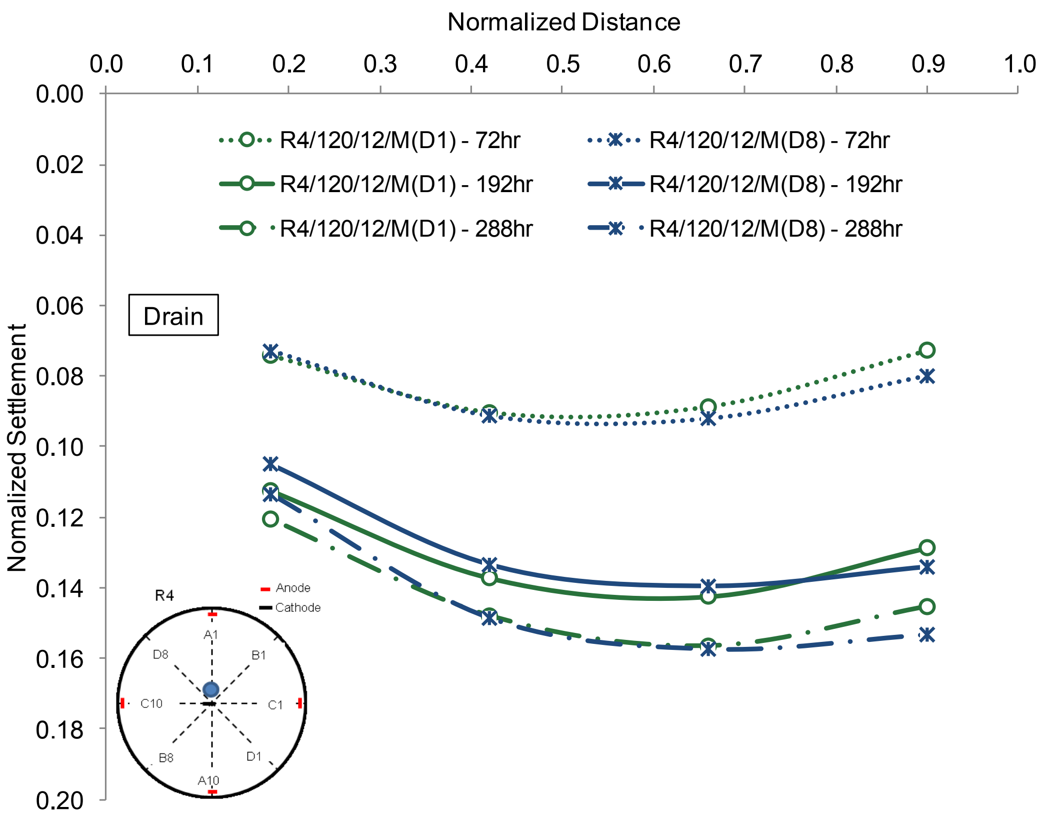
A 57: Variation in normalized settlement with time along Grid B in EO consolidation of peat in test with R4 electrode configuration at 120V/m



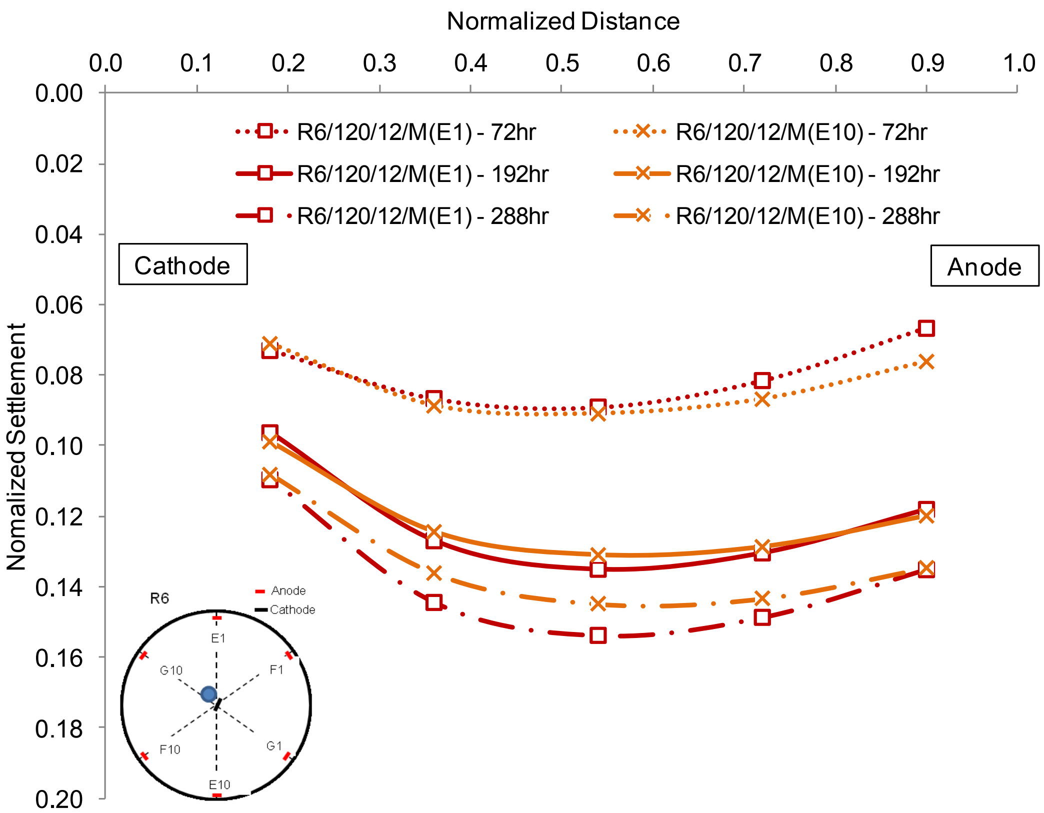
A 58: Variation in normalized settlement with time along Grid C in EO consolidation of peat in test with R4 electrode configuration at 120V/m



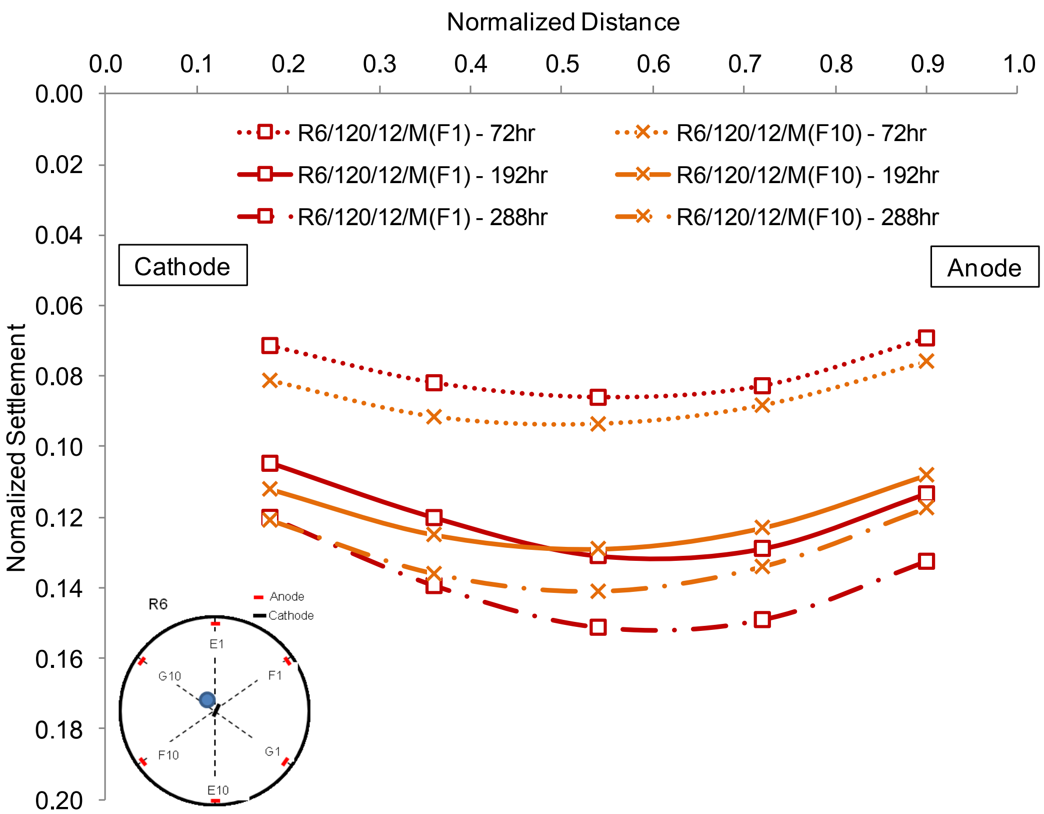
A 59: Variation in normalized settlement with time along Grid D in EO consolidation of peat in test with R4 electrode configuration at 120V/m



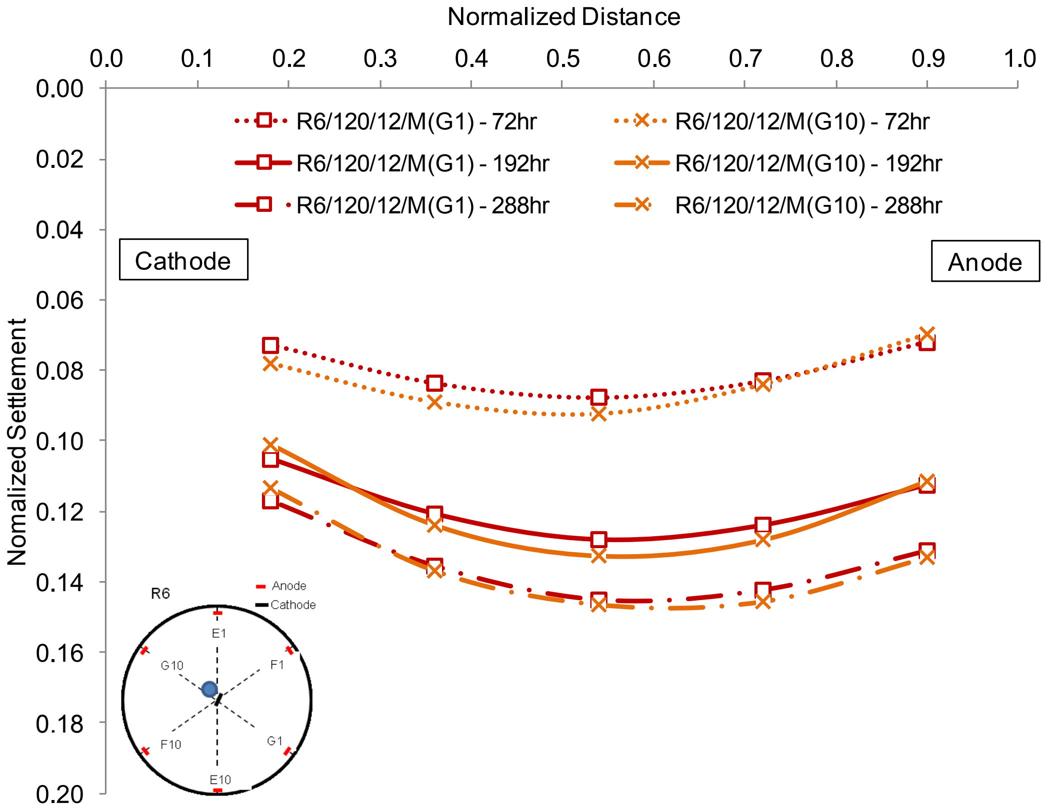
A 60: Variation in normalized settlement with time along Grid E in EO consolidation of peat in test with R6 electrode configuration at 120V/m



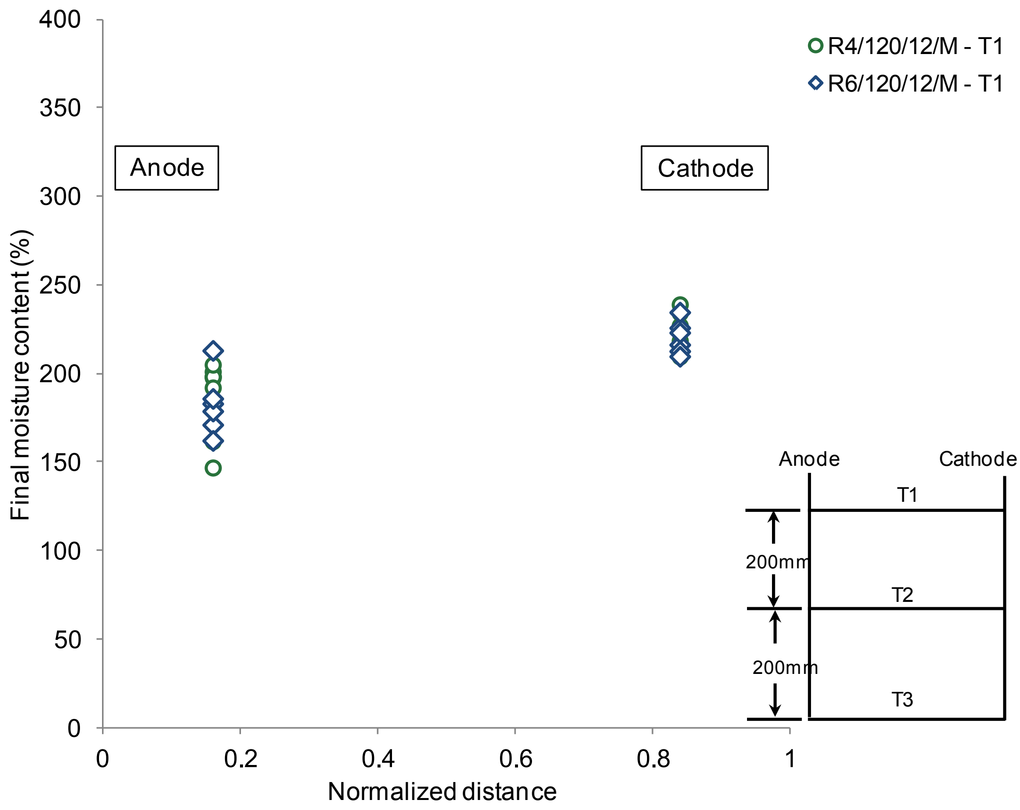
A 61: Variation in normalized settlement with time along Grid F in EO consolidation of peat in test with R6 electrode configuration at 120V/m



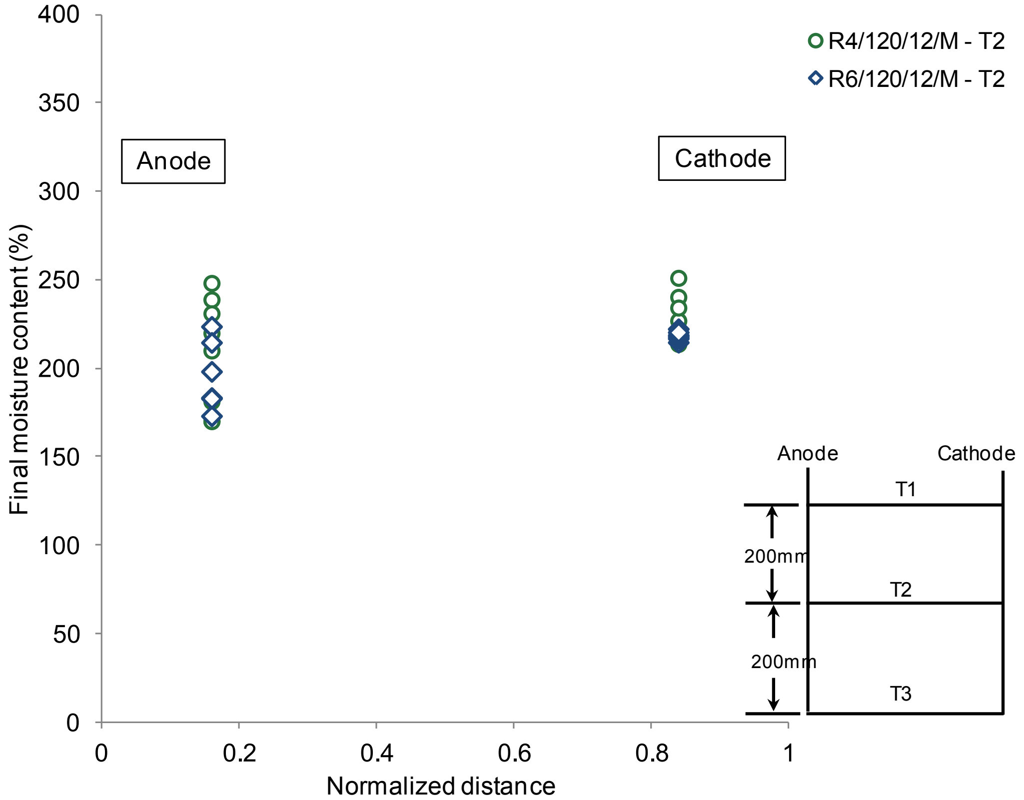
A 62: Variation in normalized settlement with time along Grid G in EO consolidation of peat in test with R6 electrode configuration at 120V/m



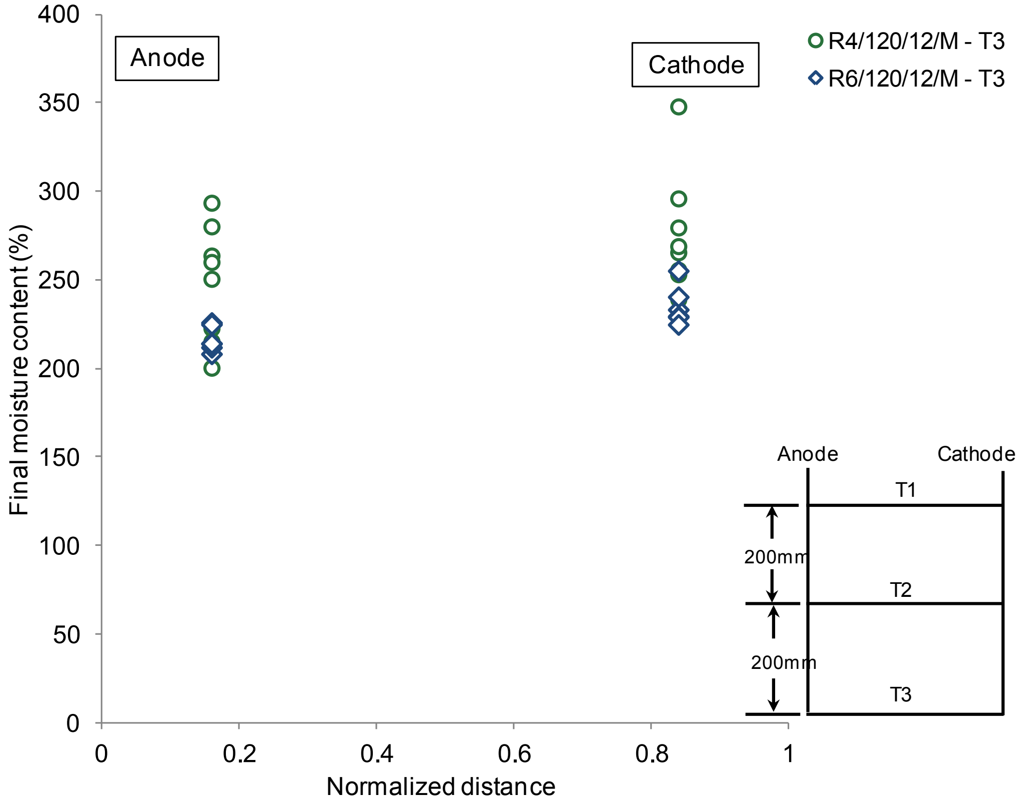
A 63: Final moisture contents at soil surface, T1, after EO consolidation with R4 and R6 electrode configuration at 120V/m



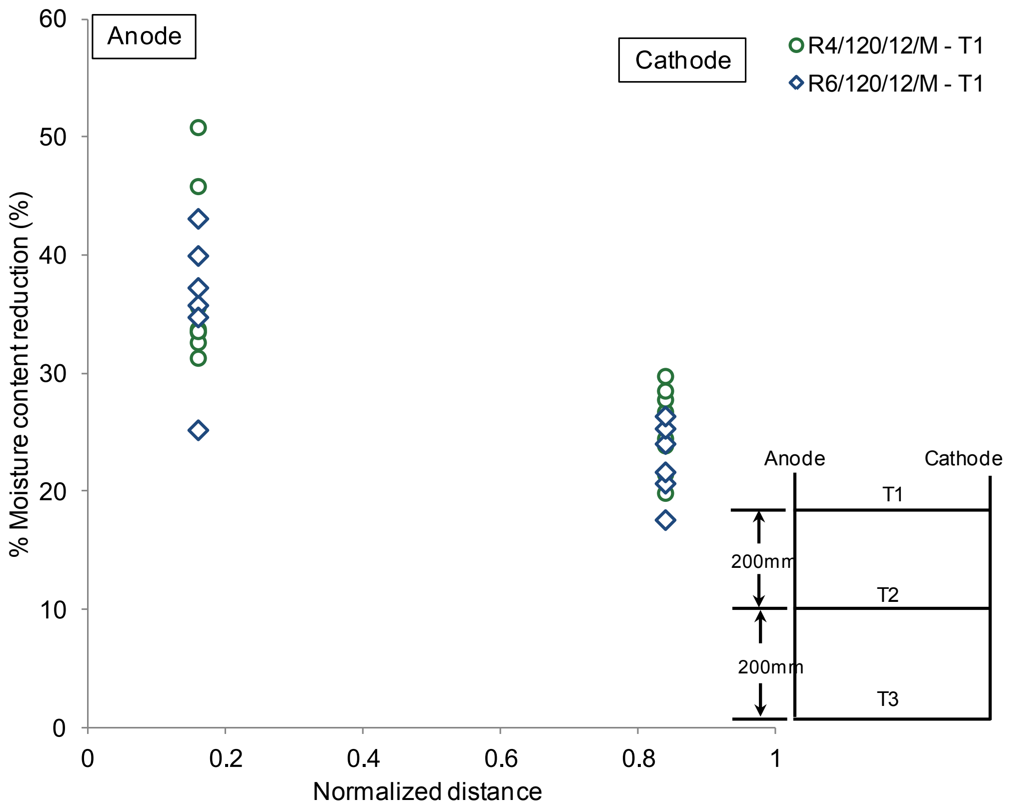
A 64: Final moisture contents at mid-depth, T2, after EO consolidation with R4 and R6 electrode configuration at 120V/m



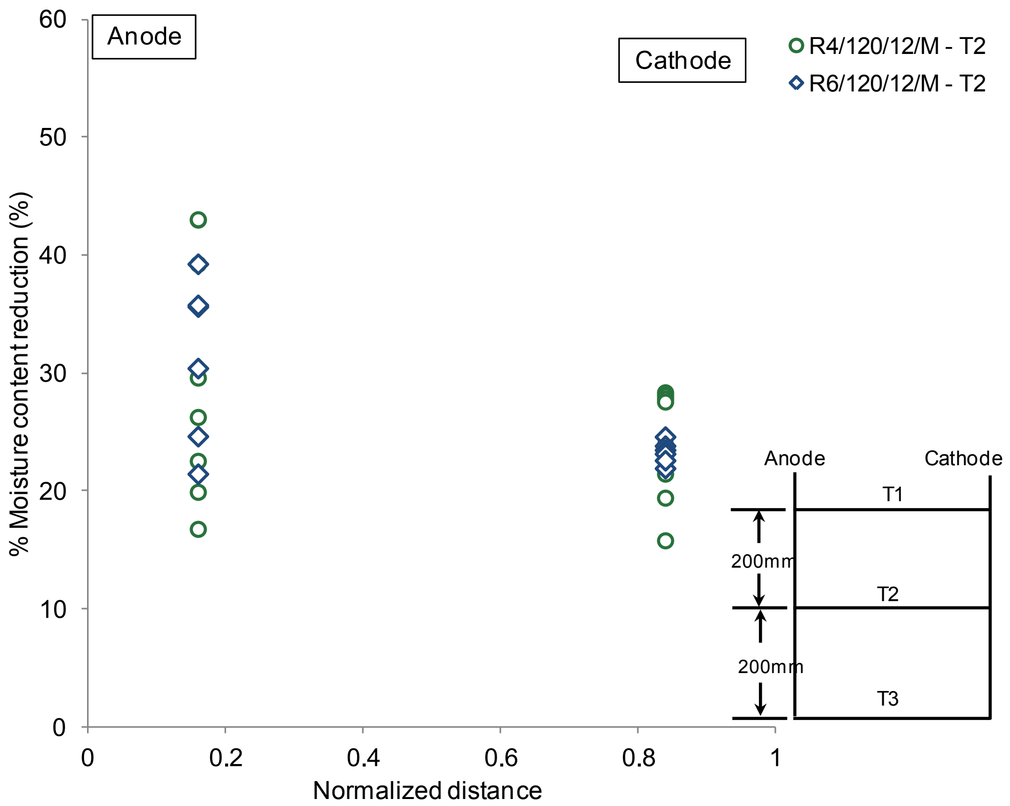
A 65: Final moisture contents at bottom of peat, T3, after EO consolidation with R4 and R6 electrode configuration at 120V/m



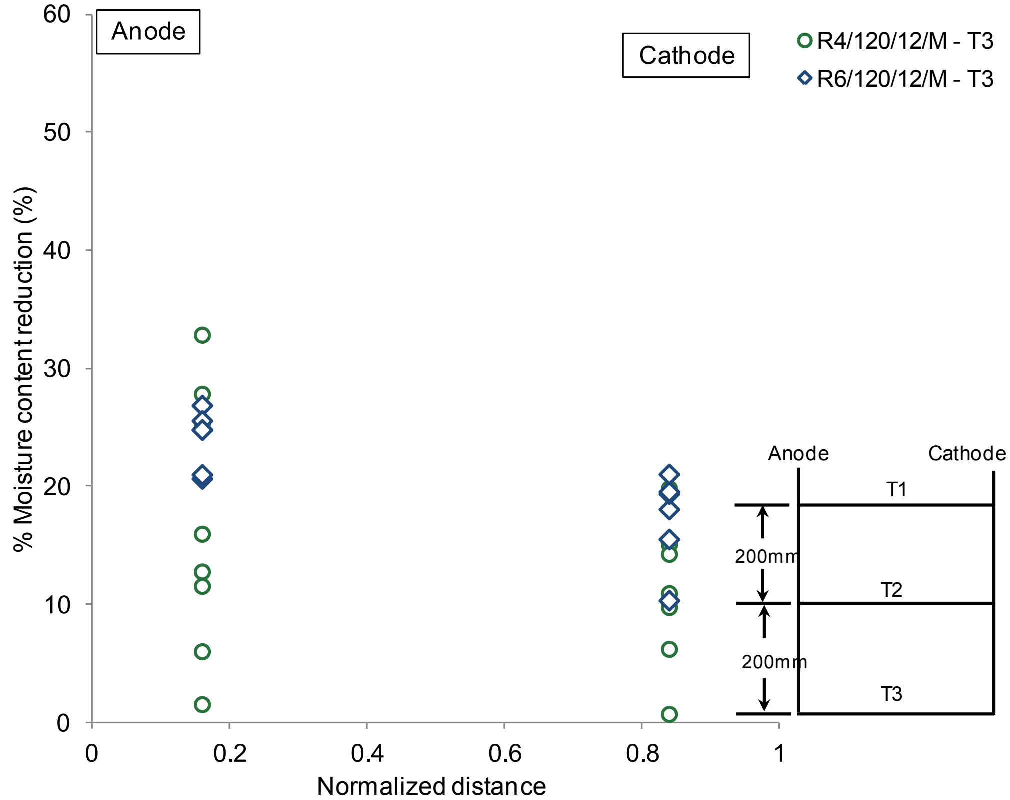
A 66: Moisture content reduction at soil surface, T1, after EO consolidation with R4 and R6 electrode configuration at 120V/m



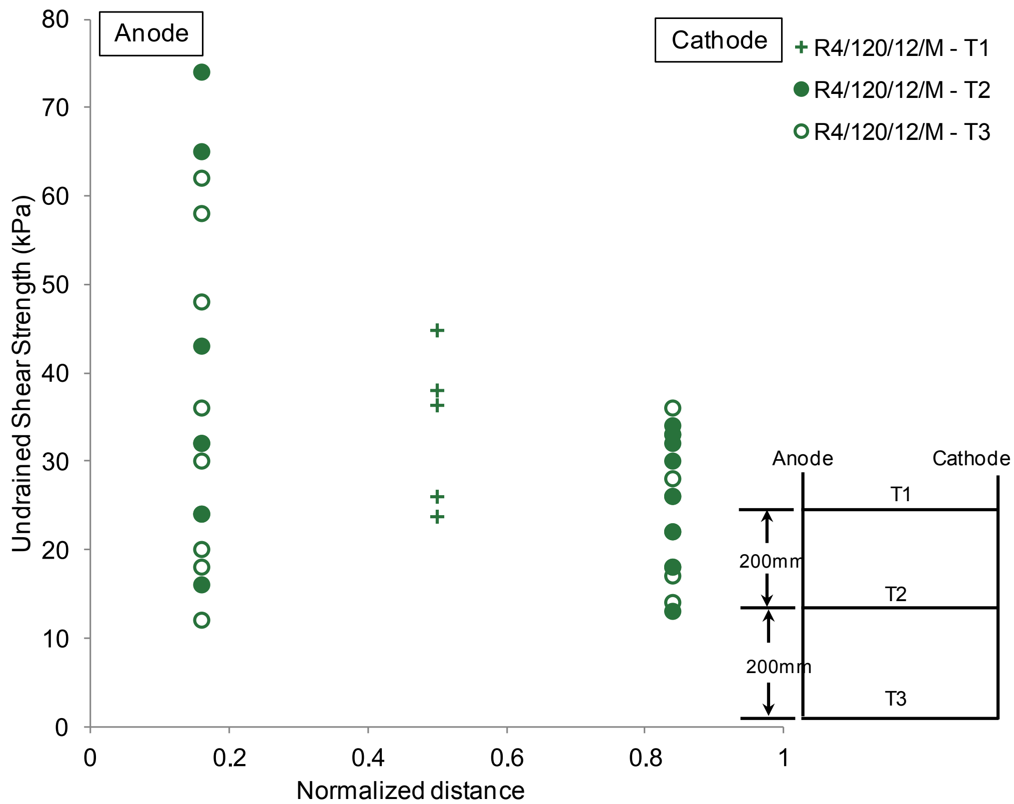
A 67: Moisture content reduction at mid-depth, T2, after EO consolidation with R4 and R6 electrode configuration at 120V/m



A 68: Moisture content reduction at bottom of peat, T3, after EO consolidation with R4 and R6 electrode configuration at 120V/m



A 69: Final undrained shear strength at surface (T1), mid-depth (T2) and bottom (T3) of peat in test with R4 electrode configuration at 120V/m



A 70: Final undrained shear strength at surface (T1), mid-depth (T2) and bottom (T3) of peat in test with R6 electrode configuration at 120V/m